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Memo

To:	Santa Cruz County, Community Foundation Santa Cruz County		
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Date:	August 31, 2021	Phone:	480-538-1545
Ref:	100076121	cc:	File
Subject:	Post-Burn Risk Analysis, CZU Lightning Complex Fire		

This memorandum summarizes the work performed by Atkins North America, Inc. (Atkins) for Santa Cruz County and the Community Foundation Santa Cruz County to provide post-burn runoff and debris flow risk information prior to the onset of the 2021/2022 winter rainy season. The project area consists of areas within Santa Cruz County (SCC) that were impacted by the CZU Lightning Complex Fire. The project area is shown in **Figure 1**. The tasks performed include data collection, field reconnaissance, modeling, and calculations. The results of these tasks were analyzed along with engineering judgement to create risk zones associated with post-burn debris and flood flows.

The CZU Lightning Complex Fire burned more than 86,000 acres in Santa Cruz and San Mateo Counties in August and September of 2020. The fire occurred in both developed and undeveloped areas and resulted in 1,450 structures lost. The fire has increased the risk for flooding and debris flows in the burned watersheds. The Watershed Emergency Response Team (WERT) and County staff have performed assessments that included post-burn risk assessments. However, further analysis is warranted to assist in community recovery.

Debris flows may contain coarse materials such as boulders and woody debris and exhibit behavior that can be different from flood flows. The purpose of this study is to provide a debris flow hazards analysis, risk mapping, and mitigation options for consideration by the County land use planning and flood control and other agencies or groups. The study area is shown in **Figure 1** and includes watersheds in Santa Cruz County impacted by the CZU Lightning Complex Fire. Note that small areas draining mainly to San Mateo County are excluded from this study.

Several varying definitions may exist for terminology associated with debris, mud, and flood flows. For the purposes of this memorandum, a debris flow is considered a fast-moving mass of loose mud, sand, soil, rock, and water that travels down a hillslope via gravity in response to rainfall, and contains sediment concentrations that are greater than 30%. A mud flow, flood flow, or muddy water flow is similar, but contains mostly water in the flow, with less than 30% concentration of sediment. Landslides are above a 70% concentration of mud, sand, soil, and rock (and subsequently much less water). The risks associated with landslides are not included in this study.

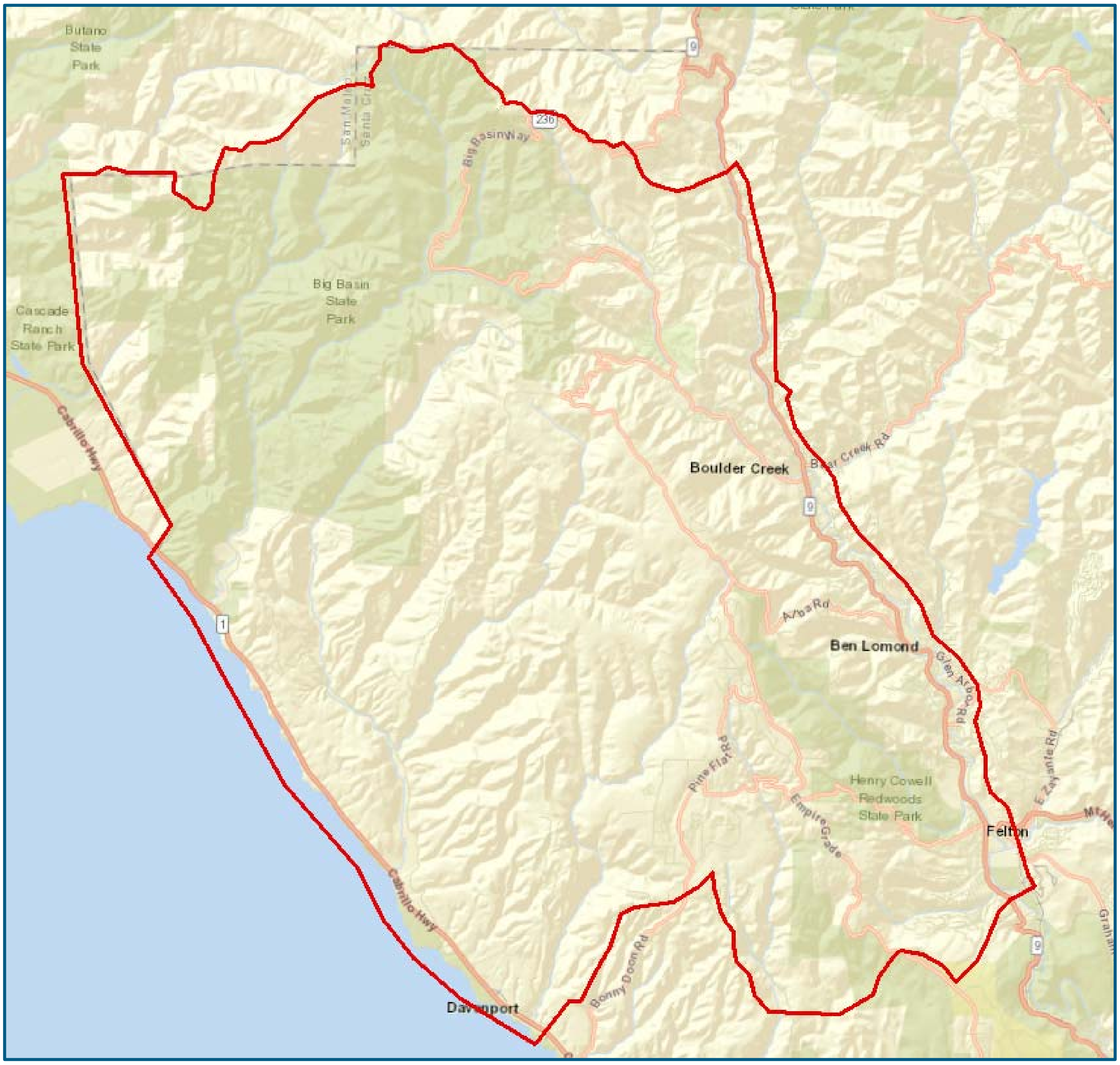

Figure 1. Study Area

Referenced Data and Research

The extensive literature and available data on the fire and various post-burn risks were reviewed and analyzed for this project. The following referenced studies were compiled and were used for the risk analysis. A complete list of reviewed literature and studies is included in the References section of this memorandum.

- Watershed Emergency Response Team (WERT) Evaluation CZU Lightning Complex, CA-CZU-005205, October 1, 2020. This report rapidly evaluated post-fire watershed conditions, identified potential values-at-risk, and evaluated the potential increased hazards for post-fire flooding and debris flows. This includes the burn area severity maps, and all associated electronic records and spatial shapefiles (WERT, 2020).

- California Geological Survey (CGS) Boulder Creek Post-WERT Study, 2020 CZU Lightning Complex Burn Area, Santa Cruz County. CGS conducted a more focused rapid evaluation of alluvial fan geomorphology and prepared maps illustrating areas potentially subject to high and low energy debris flow and flood inundation (CGS, 2020).
- Topography using QL1 LiDAR data collected in 2020 (San Mateo Resource Conservation District, 2011). The horizontal coordinate system is NAD_1983_2011_California_Zone_3_ftUS and the vertical coordinate system is NAVD88 height in feet, Geoid12B. A two-foot resolution, bare earth digital terrain model (DTM) was supplied.
- Geologic map and map databased of the Palo Alto 30'x60' quadrangle, USGS Map MF-2332, 2000. Note that almost all geologic units represented in this area have a potential for instability (USGS, 2000).
- Structure assessment records by California Department of Forestry and Fire Protection (CAL FIRE) and Santa Cruz County for damaged structures resulting from the fire (CAL FIRE, 2020).
- Maps by Santa Cruz County of the DRAFT Potential Debris Flow Hazard Area Map, Sheets 1 – 4 (Santa Cruz, 2020).
- Landslides, Floods, and Marine Effects of the storm of January 3-5, 1982 in the San Francisco Bay Region, California, edited by Ellen and Wieczorek. This compilation included numerous reports and studies on debris flows and landslides that occurred in 1982. Hand-drawn source maps included records of mass wasting events. It should be noted that mass wasting events have occurred in the watershed in response to other hazards such as earthquakes and flooding in addition to the increase in potential due to wildfire (Ellen and Wieczork, 1982).
- Soils data from USDA's web soil survey (SSURGO), land cover from the National Land Cover Database (NLCD) from 2016 (USDA, 2016).
- Statistical gridded rainfall estimates per return interval were taken from NOAA Atlas 14 (NOAA, 2014).

Additional information used in this study are listed under the References section of this memorandum.

Work performed

Atkins performed the following tasks associated with gathering and analyzing geomorphological and topological information pertinent to the risk analysis and mapping. The procedure for developing the updated risk zones is described in the Debris Flow Risk Areas section of this memorandum.

Field reconnaissance

A field review of the project area was conducted on August 17 and 18, 2021, to gather information on watershed conditions. The main purpose of this review was to assess watershed geomorphology, vegetation, evidence of historic flooding and debris flows, and development conditions.

Avulsion potential areas were examined during the field reconnaissance, including choke points as identified in the CGS report (CGS, 2020). These observations were analyzed, along with other factors, while creating risk areas. The procedure for developing the updated risk zones is described in the Updated Debris Flow Risk Zones section of this memorandum.

Exposed soils and geologic layers were observed, both on the surface and in road cuts. The formations were noted to be weathered and friable, consisting of mudstones and highly weather granitic formations. **Figure 2** illustrates a road cut exposing the Rices Mudstone layer, which can be removed easily by hand on the exposed face.

Figure 2. Road cut showing typical mudstone deposit

Photos

Photos were gathered during field investigations. The photos are transmitted electronically, in separate folders according to watershed or stream name.

Hydrologic and Hydraulic (H&H) Modeling

H&H modeling was performed for the watershed limits shown in **Figure 1**. The purpose of the modeling in this study was to provide information to further help define the risk zones and provide clear/muddy water flow estimates for inundation limits, depths, and velocities for different flow events. Due to the burned condition of the watershed, pre-burn and post-burn conditions were modeled. Return intervals modeled are the 2-, 10-, 25-, 50-, 100- and 500-year events for both pre-burn and post-burn conditions.

Note that Newtonian flow conditions are modeled (i.e., clear water with a sediment concentration of up to ~30%). Debris flows can have greater sediment concentrations up to 70%, and additionally transport large items such as trees, boulders, and other items that might interface with the flow. Note that sediment concentrations above 70% are typically considered landslides and are not covered by this study.

A greater sediment concentration can change flow properties of the runoff, with sediment concentrations between 30% and 70% termed "non-Newtonian" flows by hydraulics engineers. Non-

Newtonian flow does not follow Newton's law of viscosity where constant viscosity of the fluid occurs independent of stress. In non-Newtonian flow, viscosity can change when under force to either more liquid or more solid. It is typical for a debris flow event to have a wide range of fluid properties, and therefore it may require study of many different flow and sediment concentration scenarios. For this study, the Newtonian flow models are used to approximate non-Newtonian flow. This is performed by applying additional volume and flow to the model through estimation of post-burn runoff conditions and bulking factors. The bulking factors simulate suspended sediment by adding additional volume at the specified factor.

<u>Please note that no existing model can adequately predict a debris flow</u>, which is a complex event. Channel clogging due to large items in the flow such as boulders and woody debris may cause avulsions to occur, where flow leaves the main channel. A downed tree or transported urban debris (such as a car or shed) can completely clog a channel and force flow into the adjacent area. Once out of the main channel, debris flows can travel long distances and cause extensive damage.

Hydrologic Modeling

Due to limitations in the HEC-RAS software (USACE, 2021b) for calculating soil losses, a HEC-HMS hydrologic model (USACE, 2021a) was created to determine a uniform soil loss rate for the study area. The losses were estimated from the NRCS Curve Number (CN) method (USDA, 1986). A composite curve number was created for presumed existing conditions (pre-burn conditions) using soil types, land use, and vegetation considerations.

The CN was modified for post-burn conditions by applying a burn factor on the pre-burn conditions depending on burn severity. The burn severity was derived from the WERT study's BARC (burn severity) map (WERT, 2020), and field work and studies performed by others. No new work was performed to estimate soil burn severity. Note that the WERT report indicated that the low burn severity areas, which account for 80% of the burn area, may be underestimated due obscuring of the ground by the surviving tree canopy (WERT, 2020).

The curve number factors to represent post-burn conditions are a multiplier of 1.1 for low burn severity, 1.3 for moderate, and 1.5 for high. These factors were derived from a 2018 post-burn calibration effort performed by Atkins on the Goodwin Fire (Atkins, 2018), and similar to many US Forest Service methods to derive post-burn modifiers. The burn severity map values were intersected spatially with the pre-burn curve numbers to develop the post-burn composite curve number.

Hydraulic Modeling and 2D Methodology

The results of the hydrologic modeling were used as input into HEC-RAS Version 6.0.0 (USACE, 2021b) hydraulic models using two-dimensional (2D) flow routing routines.

Terrain

Culverts and bridges are generally assumed to be blocked by debris and modeled as a raised element following the top of road. Weirs or connections were not created for these structures. However, at some locations, this assumption was deemed to be too conservative at major structures, and the topography was hydro-enforced to allow flow through to match the width of the drainage structure. Culvert and bridge hydraulic modeling routines were not used.

Rainfall and Inflows

The "Rain-on-Grid" modeling approach was used which applies a rainfall hyetograph over the study area. Rainfall was taken from NOAA Atlas 14 (NOAA, 2014), with losses determined from HEC-HMS as described in the Hydrology Modeling section. Storm events were modeled for the 2-, 10-, 25-, 50-, 100- and 500-year events for both pre-burn and post-burn conditions for the 24-hour duration storm.

Although debris flows are often initiated by high-intensity, short duration storms, the resulting modeling using such events yield underestimation of flow and inundation areas. Therefore, the 24-

hour storm duration is used to yield better modeling results. The modeling defines probabilistic flood flows and is also used as a tool to help define potential debris flow inundation areas.

Two sources of riverine inflow were also added as flow hydrographs to the model for the San Lorenzo River and Boulder Creek. The peak inflows for the modeled return intervals were taken from the FEMA Flood Insurance Study (FIS) for Santa Cruz County, and entered as a constant inflow at the specified FIS flows. Published flows at different return intervals were used, where reported, and estimated for by interpolation for missing return intervals. A constant flow was chosen instead of a hydrograph as relative peaking timing between the local and offsite flows are not known. Therefore, it was assumed that the rivers would be running at peak flows during the time that the local watersheds peak, which is a conservative assumption. However, please note that due to the steepness and slopes of this watershed, backwater from these rivers does not affect the smaller tributaries, except within the floodplains of the rivers.

Computational Domain

The computational domain divided the study area into 7 subwatersheds based on the USGS HUC-8 boundaries (USGS, 1987). This was done for the purposes of applying different rainfall hyetographs to reflect the NOAA 14 varying rainfall estimates across the entire study area. Boundary conditions were used to transfer flow between the subwatersheds in the model. However, please note that very small areas may exist where water ponds against the computational domain. These have all been checked and are minor in nature and do not impact the results for the purposes of this study.

A cell size of 100-feet was initially specified to keep the overall model size at less than one million cell elements to facilitate computation time. Breaklines were added around channels and other features to adjust cell size and cell face orientation as needed. However, due to the steepness of the terrain, it was noted that this cell size was too large in some areas and resulted in gaps in the floodplains.

Therefore, smaller cell sizes were specified in select areas of the model where greater detail was needed, termed the areas of interest for the purposes of discussion. Refinement areas were developed around stream centerlines in the areas of interest to provide smaller cells to resolve the gaps. Stream channels with a drainage area of greater than 0.5 square miles were refined, along with other areas where additional detail was needed. Outside of the areas of interest in the larger cell areas, gaps in the inundation limits and floodplains may exist.

Roughness coefficient selection for cells were automated using the land cover type layer provided by the NLCD (USGS, 2019).

Post-burn modeling

Post-burn modeling used the increased runoff factors as described in the hydrology section. Additionally, a bulking factor of 1.5 was used to represent transported sediment and debris resulting from the post-burn condition. Roughness coefficients were unchanged from pre-burn conditions based on field examination of the watershed, which indicated that a substantial number of trees, vegetation, rocks, etc. exist in the channels in the post-burn condition.

Results

The results of the H&H modeling are provided in the following formats:

- Electronically in GIS shapefile and raster dataset formats for all return intervals
    - Inundation polygons for all studied return intervals for depths above 0.1 feet, cleaned to remove islands and disconnected shapes less than 1,500 square feet in size, and clipped to remove small, disconnected areas outside of the areas of interest.
    - Maximum depth rasters, not clipped or filtered, with values in feet.
    - Maximum velocity rasters, not clipped or filtered, with values in feet per second.
- HEC-RAS electronic models for all return intervals

Disconnected areas in the inundation polygons and rasters may exist. This is due to many potential factors, including model resolution and very low depth sheet flow conditions. While some automated filtering occurred to address the disconnections, areas may still exist.

Debris Flow Risk Areas

Debris flow risk mapping was performed for several sub-watersheds in the project area. These watersheds and/or areas are shown in **Figure 2**.

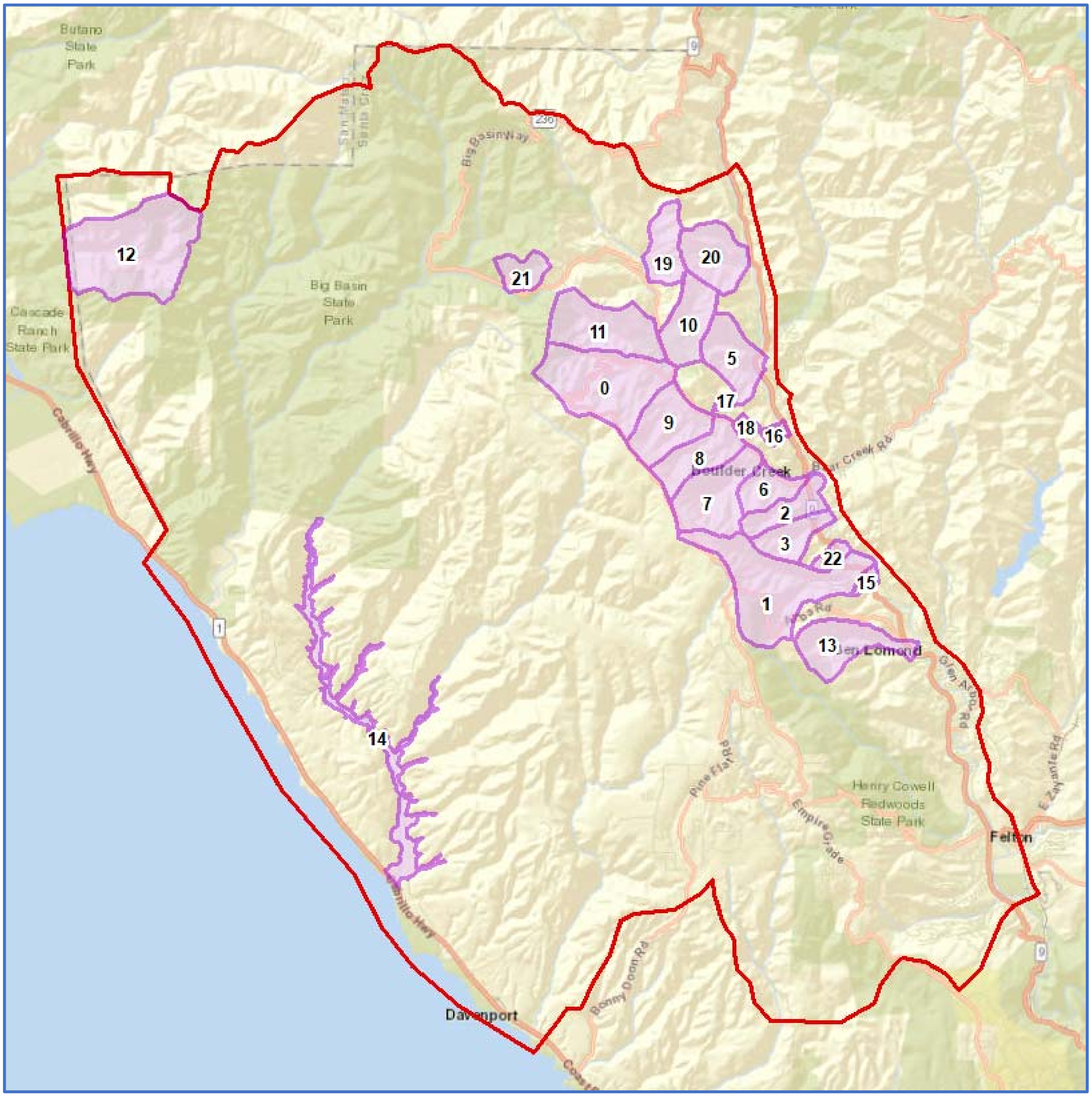

Figure 2. Debris Flow Risk Mapping Sub-watersheds

Debris Volume

Potential volumes of sediment production from a burned watershed were calculated to aid in risk zone refinement. Additionally, this volume can be used to size potential future mitigation debris basins. Volumes for the detailed study areas shown in Figure 2 were calculated using the Ventura County method for predicting the sediment production (Ventura County, 2005), where:

$$SY = 17.54(A)^{0.828} \times (ER)^{1.382} \text{ X } (FF)^{0.251} \text{ X } (SF)^{0.375} \text{ X } (K)^{0.840}$$

The definitions of the parameters are:

SY = Sediment Yield, cubic yards.

A = Area of the Watershed, square miles.

ER = Elongation Ratio, A ratio produced by dividing the diameter of a circle with an area equal to that of the watershed in square feet by the maximum watershed length measured in a straight line parallel to the main channel, also in feet.

FF = Fire Factor, The percentage of non-recovery of vegetative cover in the burned watershed. Values of the Fire Factor range from a maximum value of 100 immediately after the fire; to a value of 88 six months after the fire; to a value of 20 4.5 years after the fire; to a value of 1 7.5 years after the fire. The approach assumes a watershed is completely recovered from a burn after 7.5 years.

SF = Slope Failures. The area of the watershed in acres that is prone to slipping divided by the drainage area in square miles. For this study, a uniform factor of 50% was chosen to reflect the steepness of the watersheds.

K = Dimensionless Rainfall Factor, varies for different storm frequencies and is the product of the square of the 1-day precipitation value and the 10-day precipitation value for a given storm frequency in inches. Calculations are provided for the 10-year (10% annual chance event (ACE)), 25-year (4% ACE), 50-year (2% ACE), and 100-yr (1% ACE).

The average annual debris production (AADP) can be estimated as a percentage of the 50-year (2% annual chance) event per the Ventura County manual (Ventura County, 2005). This number can be used to estimate yearly maintenance sediment removal quantities. This is estimated as a range of 3 to 13% of the 50-year calculations, with finer grained soils having a lower annual contribution than coarser grained soils. The watershed soils were noted to be relatively fine grained, and 6% was chosen to estimate the AADP for this watershed.

Table 1 – Ventura County Method Sediment Volume Calculations

Watercourse	ID	Sediment Volume, ac-ft, by event				
		10%	4%	2%	1%	AADP
Jamison Creek	0	12.65	19.96	26.95	35.34	1.62
Clear Creek	1	17.24	27.79	38.11	50.80	2.29
Harmon Creek	2	3.31	5.34	7.33	9.76	0.44
Molaski Creek	3	3.93	6.34	8.70	11.59	0.52
Spring Creek	5	6.88	11.03	15.07	19.99	0.90
St. Francis	6	5.95	9.58	13.13	17.49	0.79
Boulder Brook/Forman Creek	7	9.89	15.84	21.61	28.66	1.30
Silver Creek	8	7.64	12.21	16.62	21.98	1.00
Leafwood	9a	3.09	5.10	6.52	9.11	0.39

Watercourse	ID	Sediment Volume, ac-ft, by event				
		10%	4%	2%	1%	AADP
Acorns	9b	3.02	4.72	6.50	8.44	0.39
Fallen Leaf	9c	1.71	1.82	3.69	3.26	0.22
Kings Highway/Country Club	10	5.70	9.10	12.38	16.35	0.74
Hare Creek	11	6.56	10.39	14.06	18.46	0.84
Whitehouse Creek	12	10.01	16.04	21.86	28.88	1.31
Marshall Creek/Hubbard Gulch	13	5.77	9.30	12.78	17.07	0.77
Scott Creek/Swanton*	14	n/a	n/a	n/a	n/a	n/a
Forest Way	15	0.83	1.34	1.85	2.47	0.11
Riverdale	16	2.94	4.74	6.51	8.67	0.39
Burnside	17	0.42	0.66	0.90	1.20	0.05
Virginia Avenue/Ridge Drive	18	1.22	1.96	2.68	3.57	0.16
Memory Lane	19	3.10	4.96	6.78	8.98	0.41
Dry Well/Ramble	20	6.50	10.45	14.30	18.98	0.86
Big Basin	21	2.93	4.66	6.31	8.29	0.38
Monan/Alta Via Road	22	1.58	2.55	3.50	4.67	0.21

*Not calculated due to size of drainage area.

Triggering Rainfall

Debris flows and landslides are known to be triggered by rainfall events exceeding certain intensity and duration thresholds. Triggering precipitation thresholds were developed in the CGS report, and no additional work was performed in this study related to updating these thresholds. Please note that recent studies on California fires (McGuire et al, 2019) indicate a roughly 40% increase in the 15-minute rainfall intensity-duration threshold associated with debris-flow initiation from post-fire year 1 to post-fire year 2.

Spatial compilation

Numerous spatial data features were compiled and viewed using ESRI's ArcGIS geographic information system software (GIS). The purpose of this compilation was to provide data on factors known to influence debris flow initiation and behavior. This data was examined and analyzed, along with other processes as described in this memorandum and using engineering judgement, to produce the risk zone mapping.

- <u>Slopes exceeding 18 degrees</u>. Previous studies indicate a higher debris flow potential originating from slopes steeper than 18 degrees (USGS, 1997). This is an extremely steep watershed. Note that the upstream watersheds in the project area exceed this threshold in most areas.
- <u>Alluvial fan apexes</u>. Alluvial fan apexes or areas that may act similarly based on topology and/or morphology may result in sediment deposition or flow avulsions. They provide a morphologic clue to potential alluvial or debris deposition areas. The topography was examined for typical fan formation clues, such as radial contours extending downstream from a mountain front. These areas are often considered at risk for flood and debris flows due to uncertain flow paths.

- Potential avulsion areas based on topology and/or morphology. Areas subject to avulsions or uncertain flow paths may result in debris flows occurring outside of the main watercourse channel. Avulsions may also occur if structures are blocked or deposition occurs during an event. Locations for potential avulsions were identified from the CGS report, and the H&H modeling, which modeled blocked culverts and potential breakout areas. Note that avulsions may occur rapidly during an event at almost any location, whether predicted or not, due to deposition or blockages. These areas have an identified greater potential, but avulsions may occur elsewhere, even if not predicted in this study.
- Historical mass wasting and debris flow extents. Evidence of previous debris flows is an indicator that debris flows may again occur at the same locations in the future. The 1982 Ellen and Wieczork study was examined. Additionally, Santa Cruz County indicated spot locations where geologic investigations were performed and identified evidence of previous debris flows during the field reconnaissance.
- Narrow canyon side drainage channels. Debris flows are known to originate in narrow canyon side drainage channels (USGS, 1997). Note that many locations in the upstream mountainous areas were not individually evaluated for debris flow potential; however, all upstream drainage channels in the mountainous regions may be at risk for debris flows.
- Stream order hierarchy. Stream order has been classified for debris flow potential by USGS (USGS, 1997) and was used for the streams in the study area. Note that the results of this exercise confirmed the potential for debris flows on the contributing tributaries as they are generally located higher up in the stream order hierarchy. The larger, parent streams such as the San Lorenzo River are not likely to propagate debris flows downstream in the main river channels for significant lengths.
- Draft County debris flow risk areas. The draft debris flow risk areas developed by CGS and the County in 2020 were referenced and re-evaluated during this study.
- WERT Landslide Map. The landslide compilation map shown as Figure 5 in the WERT Report (WERT, 2020) was referenced as an indicator of slope instability. Due to the steep slopes prevalent throughout this watershed, a risk for landslides exists. However, note that landslide and landslide-generated debris flow risk was not evaluated in this study.
- CGS Report Debris Flow Probability Calculations. The CGS Report used USGS probability equations and modeling to predict the likelihood and volumetric yield of potential debris flows in the study area. The combined hazard classification for each watershed was referenced, where both high and moderate basin hazards for the 15-min 40 mm hr-1 event were included for a risk polygon in this study.
- Terrain. The morphology of the terrain was used to identify areas that may be subject to a higher risk based on landform. This evidence is found in depositional features, fans, landslides, and over steepened slopes.
- H&H model results. Since no model exists that can perfectly predict a debris flow, the results from the 500-year (0.2% annual chance event), post-burn H&H model with the 1.5 bulking factor were reviewed as a representation of a potential debris flow inundation area. The results of this model scenario for water surface elevations, depths, and velocities were examined to determine potential hazard areas. See further discussion on this in the Hydrologic and Hydraulic Modeling and Debris Flow Risk Areas sections of this report.

Debris Flow Risk Areas

Risk areas (or zones) were created for the study area using the information gathered and analyzed as described in this memorandum. Spatial files and work maps at 1:500 scale (attached to this memorandum) present the results. The following zones were created:

- Primary debris flow path (model predicted). These areas are the predicted primary debris flow path within the detailed study areas. They were created from the H&H model inundation areas resulting from the 500-year, bulked, post-burn condition (discussed in the Spatial Compilation section of this memorandum). These areas are considered as the main transport corridor for water, mud, and/or debris flows and are often hazardous. They typically have higher velocities and depths than the surrounding areas within the respective watershed.

- Uncertain debris flow path, potential breakout flow. These are areas that may be subject to alluvial, breakout, or avulsions from the primary debris flow path and main channel. These flows, once they leave the channel, may continue to flow on the surface but not return to the main channel. This condition is not reflected in the hydraulic modeling as the model cannot account for changes that may occur during the flow event (e.g., a fallen tree blocks a drainage which causes flow to avulse to an adjacent area). Therefore, wider high-risk areas may exist to reflect an unknown flow direction or break out that originates in the upstream areas.
- Inundation area (water, mud, and/or debris flow), model predicted. These areas are the predicted primary flow path outside of the detailed study areas. They were created from the H&H model inundation areas, but no further study was done to determine potential characteristics of the flow. These areas are considered as the main transport corridor for water, mud, and/or debris flows, and avulsions were not studied. This layer was spatially filtered to remove flooding resulting from less than 0.5 square miles in drainage area; remove flooding depths less than 0.1 feet; cleaned to remove islands or disconnected flooding less than 1,500 square feet; and a minimum of 10 feet of width in the inundation area along the channel thalweg. Although the spatial cleaning was performed, areas of disconnected flooding or islands may still appear.
- FEMA Effective Flood Zones. The effective FEMA flood zones are shown as an overlay to the zones developed in this study. The FEMA flood zones are not being revised with this study.
- Detailed study area. Due to the size of the burned area, select areas were chosen for detail study, as shown by this zone. The areas within this zone were evaluated for debris flow or clear/muddy water flow, and for uncertain flow paths. These areas may contain other zones to reflect potential hazards (as previously described). Otherwise, the areas within the detailed study area that are not covered by other zones may be considered at lower risk for damaging debris or flood flows.
- Study and model limits, outside of detail study area. The area shown in Figure 1 of this memorandum which included the H&H model, but not subject to additional study. Unless covered by one of the zones described previously, hazards are unknown and unstudied.

The data and results, including the previously described work tasks, were georeferenced using ArcGIS. Risk zones were created based on data analysis following the methodology described in this memorandum combined with engineering judgement.

Finally, it should be noted that all areas within the study limits may subject to some degree of debris flow, flooding, and landslide risks regardless of the risk zones defined in this study. The watershed has a history of landslides and debris flows. This indicates that a risk of debris flows in the area is present at all times should a significant or intense rainfall occur.

Debris flows may occur outside of the mapped risk zones. Due to the complex nature of debris flows and the uncertainty in the data and assumptions used, actual areas of future debris flows may not exactly match the risk zones produced in this study.

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