Post-wildfire sediment transport modeling versus field observations: Northern Arizona case studies

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Abstract

Post-wildfire floods are receiving greater attention as the urban-forest interfaces become more common and as wildfires have increased due to record drought in the American Southwest. Sediment sourcing, transport, and deposition in the post-fire environment has also received attention due to the large amount of property damage and risk of life caused by debris flows and concentrated sediment flood flows. This study provides a series of sediment model predicted outflows based on MUSLE and the WARSSS suite of models that included: ERMIT, BANCS, and FLOWSED/POWERSED for the 2019 Museum Fire watershed (Spruce Wash), 2010 Schultz Fire (multiple watersheds), and preliminary observations from the 2022 Pipeline Fire (Schultz Creek and multiple watersheds on the eastern flank of the San Francisco Peaks). A comparison is also provided for the cloud-based WEPP post-fire sediment model. The modeled results are compared to flood observations that provide a comparison of the models to real-world events. Empirical evidence from four floods in 2021 indicated 11,000 tons of sediment yield to city neighborhoods, the WEPP model provided an estimate of 4300 tons/year, MUSLE predicted 5400/tons per year (based on the four events), and the WARSSS suite of models predicted 17,000/tons per year.

Introduction

Post wildfire flooding at the urban-forest interface is an increasingly important issue for the health and safety of millions in the American West. The development of neighborhoods directly adjacent to forest lands under severe drought conditions creates hazards not just to widespread burning but flooding in the aftermath of those fires. While the changes in hydrologic properties of watersheds after severe wildfires are relatively well known, there is now a need to rapidly assess and mitigate issues following a fire in order to prevent or lessen impacts to safety and property damage.

This paper explains sediment prediction methodologies successfully utilized for several fires in the Flagstaff, Arizona area to predict sediment quantities as well as flow paths and sedimentation areas for the Schultz Fire (2010), Museum Fire (2019), and Pipeline Fire (2022). These methods have successfully guided mitigation efforts for the Schultz and Museum Fires. In addition, we provide empirical observations of the validity and accuracy of these methods under these conditions. While the methods were utilized on all three fires, empirical comparisons to modeling efforts are focused on the Museum Fire due to page restrictions. All measurement units are presented in Standard English instead of scientific units due to the applied nature of this study. A companion paper provides the hydrology and hydraulic modeling that was developed concurrently with this sediment risk study (Schenk et al. 2023).

Study Site

Flagstaff, Arizona lies at the edge of the dormant San Francisco Volcanic Field including the San Francisco Peaks, Dry Lake Hills, and Mount Elden. The local watersheds are generally hydrologically complacent unless disturbed with extremely low rainfall-runoff ratios due to local geology (weathered dacite, cinders, and karstic fractured limestone), vegetation (dense *Pinus ponderosa* forest), and relatively deep soil organic layers (Youberg et al. 2019; Schenk et al. 2021). The Spruce Wash watershed is an ephemeral tributary to the Rio de Flag, another ephemeral watershed that drains the southern portions of the San Francisco Volcanic Field. The Spruce Wash watershed drains the six dacite intrusive hills that make up the Dry Lake Hills feature as well as the western portion of Mount Elden, a larger protuberance of the same orogeny (Holm 2019; Schenk et al. 2021). A previous USGS study observed a peak flow of 5 cubic feet per second (CFS) in the Spruce Wash watershed over a period of 11 years (Hill et al. 1988) despite a watershed contributing area of greater than 5.6 square miles.

The Museum Fire occurred in July 2019 over 2000 acres on the steep, mountainous slopes of Dry Lake Hills and Mount Elden, both of which are immediately uphill of established residential areas of Coconino County (CC) and City of Flagstaff (CoF; Figure 1). Mount Elden Estates (MEE) is a rural residential area and is the uppermost residential area within the Spruce Wash Watershed. Approximately one mile downstream and separated by open U.S. Forest Service (USFS) land are the urban residential areas of Paradise/Sunnyside, which are within the CoF city limits. MEE is located on flatter slopes near the base of Dry Lake Hills on the leading and lower edge of a previously inactive alluvial fan (activated post-fire, previously complacent; Fulé et al. 2023). Paradise/Sunnyside are on the toe of inactive alluvial fans and adjacent to the broad, ephemeral, and formerly unchannelized Spruce Wash. Prior to the Museum Fire, the Paradise/Sunnyside neighborhoods had one defined channel/pipe system and surface water flow seldom occurred within these existing channels. Up gradient on USFS land, ephemeral surface flows were spread over wide alluvial fans (areas of sediment deposition) and were easily absorbed into the unconsolidated sediment. Consequently, surface water flows within the channels were primarily from stormwater runoff during normal precipitation events from local CoF streets.

The Museum Fire burned in July-August 2019 and for the duration 2019 and 2020, the Flagstaff region saw record low summer monsoonal rain with no substantial post-fire impacts. Initial flooding occurred during the above average summer monsoon season of 2021, resulting in several debris flows high within the Museum Fire watershed and four significant floods (Porter et al. 2021; Schenk et al. 2023). Post-fire flooding resulted in vast amounts of sedimentation in downstream residential areas as existing drainage features and channels were overwhelmed with post-fire sedimentation.

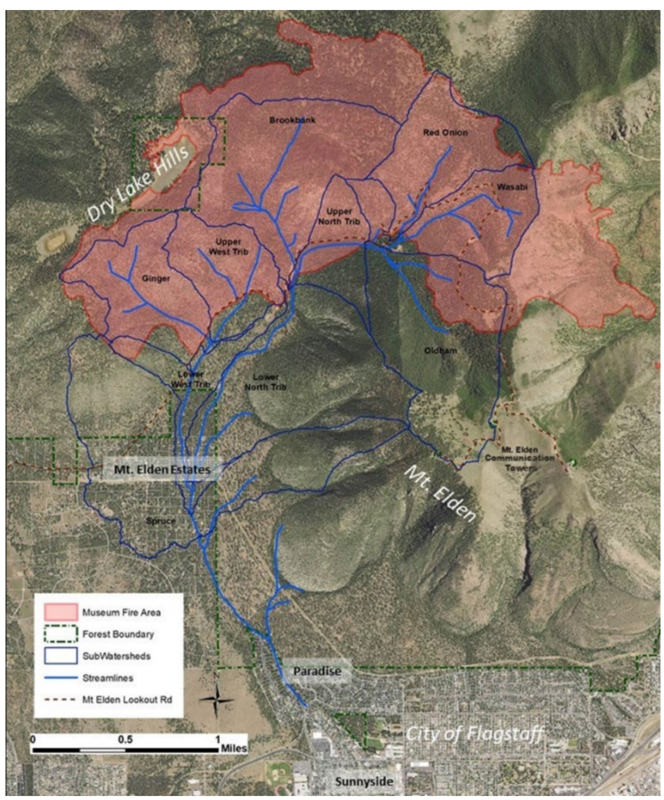

Figure 1. Overview map of the 2019 Museum Fire watershed (Spruce Wash), sub-tributary names, and locations of impacted neighborhoods. The City of Flagstaff is located in north-central Arizona on the edge of the Colorado Plateau.

Methods

The mixed methods for understanding changes in post-fire discharge and sediment sourcing and transport in a degraded watershed need to be related to each other at various scales to understand how they might impact populated areas. Both storm based and average annual predictions are helpful in understanding the sediment and discharge changes.

Flood Flow Modeling

Post-wildfire flood modeling was completed in August 2019 and was based on a 2-D numerical model created in FLO-2D (JE Fuller 2019; JE Fuller 2022). Initial flood modeling was completed at a 20 ft grid scale using 2015 lidar elevation data, subsequent modeling was completed at a 5 ft grid scale using a fall 2019 lidar elevation dataset. All modeling indicates an approximate 10 to 100 times (one to two orders of magnitude) increase in runoff depending on rain event, more information is provided in the companion paper (Schenk et al. 2023).

Sediment Modeling

The purpose of this sediment budget analysis is to **a)** assess the geomorphic state of all post-fire impacted channels within the watershed, **b)** estimate Spruce Wash watershed's annual and precipitation event-based sediment yield, **c)** determine the sediment transport of channels in their current state (fall 2021) and after treatment (2022), and **d)** develop treatment options capable of altering the downstream sediment delivery.

This sediment budget analysis focus on quantifying relative sediment sources relating to channel and hillslope erosional processes. To accomplish this, the Spruce Wash watershed within the Museum Fire burn scar was divided into sub-watersheds to identify problematic, high-sediment yield areas. Areas downstream from high sediment yield areas were identified as work areas for sediment control practices that have the greatest impact on limiting downstream sediment transport.

Methods were based on the Watershed Assessment of River Stability and Sediment Analysis (WARSSS) (Rosgen 2009), which is the same method successfully used for the 2010 Schultz Fire post-fire sediment predictions (NCD 2012). WARSSS is designed to identify the location, nature, extent, and consequences of land use impacts on sediment and understand the cause of watershed impairment. This approach was developed for application on large watersheds and is practical for the Museum Fire because it uses previously proven, rapid screening field observations that integrate hillslope, hydrologic, and channel processes. The analysis focuses on average annual yield of sediment rather than event based analyses. The average annual yields do not ignore sediment delivery from large flood events but take into account the overall frequency of these types of flows, based on a 30 year climate average. This annual average sediment yield is ideal for understanding watershed function and developing watershed restoration practices post-disturbance.

The WARSSS method relies on estimating bank erosion using the Bank Assessment of Non-Point Source Consequences of Sediment (BANCS) model and can quantify bank erosion rates and sediment supply for years with normal discharge patterns Average annual hillslope erosion is estimated using the Erosion Risk Management Tool (ERMiT; Robichaud et al. 2014). The Modified Universal Soil Loss Equation (MUSLE) (Williams 1975) is utilized to estimate sediment supply from hillslopes during specific precipitation events. Discharge for these events were estimated by JE Fuller, Inc as part of their post flood modeling efforts (JE Fuller 2019; Schenk et al. 2023). The MUSLE estimates are provided here as a reference point for larger events. Direct comparison of the different methods is difficult. While post-fire hillslope erosion will diminish over time with natural recovery, sediment bank contributions are expected to continue at high rates for many years due to post-fire channel evolution processes which tends to widen incised channels (Benda et al. 2003; Hupp and Simon 1991).

Sediment transport estimates are used to look at how supplied sediment can transport through the channel system. Sediment transport modeling used the FLOWSED/POWERSED platform in the RiverMorph software and provided estimates of average annual sediment transport through a specific cross section of channel given an annual flow scenario (Rosgen 2009). Estimates of sediment supply into a reach can be compared within the reach to aggradation or degradation for both existing and proposed design. This analysis is sensitive to several data inputs including annual flow duration curves (based on watershed size), bankfull discharge, suspended sediment and bedload sediment rating curves, channel configuration and slope. These data are difficult to obtain for ungauged ephemeral systems. We utilized sediment rating curves and dimensionless flow duration curves developed during the 2010 Schultz Fire sediment analysis which were derived from regional data and research from the Beaver Creek Research watershed effort (Natural Channel Design 2012). Utilization of this previously developed data significantly shortened the duration of the study and reduced the level of effort required to produce meaningful results.

Once problematic, high-sediment yield areas are identified, sediment transport analyses are conducted at specified downstream, proposed work areas in the Spruce Wash watershed. In addition to providing an analysis of sediment transport across channels in their current state (fall 2021), an analysis of sediment transport across a conceptualized design channel was used to understand the feasibility of altering the downstream sediment delivery and was based on the upstream sediment supply.

Assessing the Geomorphic Condition of Channels

BEHI data collection- Bank erosion hazard index (BEHI) surveys were used to qualitatively evaluate all eroding channels within the Spruce Wash watershed, (Rosgen 2002; Figure 2). During BEHI surveys, data was collected by teams of two field staff on tablets, this enabled the user to rapidly tabulate and georeference all field data on pre-formatted field forms. Collected data consists of channel bank height (left and right bank), channel and bank material, length of channel, vegetation and root density, bank slope angle (left and right), valley and stream type classification (Rosgen 1996), and near bank stress (NBS). Collected field data was manually checked for quality assurance and control using ESRI ArcGIS geospatial software.

Channel Surveys- detailed geomorphic field surveys were conducted to accurately assess the Spruce Wash channels in their current condition. Channel geomorphic surveys were completed proximal to proposed work areas (i.e. flood mitigation capital improvements) to accurately model sediment transport through channels and assess channel characteristics. Twenty seven (27) cross sectional surveys, longitudinal channel profiles, and pebble counts were completed to evaluate the channel slope and characteristics of specific channel reaches.

Figure 2. Natural Channel Design LLC staff completing the BEHI analysis at a typical channel cross-section in Spruce Wash.

Estimating Sediment Yield

<u>Channel Sediment Yield</u>- The BANCS model was used to estimate annual sediment yield (Rosgen 2002).

Bank Assessment for Non-point source Consequences of Sediment (BANCS)-BEHI data collected during the geomorphic assessment of the channels was used in the BANCS model, which is a part of the

RiverMorph software package. The BANCS model utilizes BEHI and NBS survey data to estimate sediment supply from channel bank sources and yields a sediment supply in tons (Standard English) per year. The BANCS model provides reliable estimates of bank erosion but can underestimate bank erosion rates resulting from higher-than-normal flooding and overestimate rates from years with very low peak flows (Rosgen 1996). Channel sediment supply was converted to tons/year/longitudinal foot for all evaluated reaches and then graphically displayed with ESRI ArcMap.

Hillslope Sediment Yield- The ERMiT and MUSLE model were used to estimate hillslope sediment yield. The ERMiT model predicts sediment yield annually while the MUSLE modeled is based on precipitation events (storm-based).

Erosion Risk Management Tool (ERMiT)- The ERMiT models uses soil burn severity, vegetation type, rock content, hillslope gradient, soil type, hillslope length, and annual precipitation to model sediment yield (tons/year) up to five years post fire. For the scope of this analysis, 2021 was used as the second-year post-fire. Therefore, only years 3 (2022), 4 (2023), and 5 (2024) sediment yield were modeled. To capture the variability in hillslope impacts, the Museum Fire watershed was subdivided into sub-catchments using watershed delineation in ESRI ArcMap. Each catchment was evaluated individually for its sediment yield.

Modified Universal Soil Loss Equation (MUSLE)- The MUSLE is based on the Universal Soil Loss Equation (USLE) but utilizes transport efficiency and soil erodibility. For the post-fire watersheds, the MUSLE model is particularly useful for modeling post-fire sediment yield because soil erodibility increases due to hydrophobic, ash laden soils, and transport efficiency increases due to increased runoff from decreased infiltration and retention. The MUSLE model input for post-fire situations requires instantaneous peak discharge and total volume of 1", 2" and 3" precipitation events in addition to watershed area, slope, and soil erodibility. Unlike the ERMiT model, the MUSLE model predicts event-based sediment yield in (Standard English) tons/event. Soil erodibility (K values) were estimated for low, medium, and high erodibility at 0.29, 0.545, and 0.8 respectively. The crop factor (C value) was estimated at 0.003 for forested area and the slope type (P factor) was inputted as 1 to indicate steep slope. Since the P factor does not provide a measure of the slope the LS coefficient (slope length) was set at 0.5 to account for steep slopes.

Observed Sediment Transport and Aggradation

Observed sediment transport and aggradation were collected from CoF staff during 2021 flood events (three in July and one in August). Sediment and debris were measured qualitatively using photographs of known cross sections as well as landfill tipping fees for sediment and debris removed from the channel and streets post-event. Landfill tipping fees were used as a surrogate for sediment deposition mass, as the landfill calculates fees based on precision scale measurements of truck loads (Standard English tons). Each truck load of flood related sediment was noted for potential Federal and State disaster reimbursement. A remote sensing exercise was also conducted using the fall 2019 and fall 2021 lidar flights and the cut/fill tool in ESRI ArcMap (lidar datasets available on the USGS National Atlas portal for Coconino County – Flagstaff region). The GIS output provides an empirical comparison to the modeling results.

Evaluating Sediment Transport and Retention

FLOWSED/POWERSED, which is part of the RiverMorph software package, was used to model sediment transport through channels in their current condition and through conceptual redesigned channels. Based on preliminary sediment yield analyses, FLOWSED/POWERSED was modeled at eight proposed work areas (Figure 3). Each analysis consisted of an upstream sediment source cross-section and a proposed work area cross-section. Upstream sediment source geometries were obtained from previously completed geomorphic surveys. Each analysis was iterated using the same upstream sediment source cross-section and a conceptual design cross-section. The design cross-section informed the final work area cross-section and was drawn in RiverMorph to incorporate a best practice design that promotes sediment retention. For each model run, FLOWSED and POWERSED required the following inputs: bankfull cross-sectional area (ft^2), Manning's n value, bankfull discharge, slope (ft/ft), suspended sediment (mg/L), measured bankfull bedload (lb/s), a flow duration curve, and a sediment rating curve comparison.

WEPP model runs were completed using the WEPPcloud online toolkit to compare with the WARSSS suite of models presented above. WEPP (Watershed Erosion Prediction Project) is a standard post-wildfire sediment tool for the US Forest Service and now includes an online modeling tool based on available topography, soils, and climate data (Lew et al. 2022). The modeling domain is largely based on the Soil and Water Assessment Toolkit (SWAT) methodology with adjustments based on empirical relations since the initial SWAT development (Dobre et al. 2022). The post-fire "disturbed" WEPP model was populated using the USFS BAER team soil burn severity georeferenced raster file for the Museum Fire (available through the USFS Inciweb portal) and model runs were completed using the Cligen precipitation toolbox with a PRISM modified climate application (see Dobre et al. 2022 and Lew et al. 2022 for more information). The model outlet downstream condition was selected at that Spruce Wash entry into the CoF neighborhoods (Linda Vista Avenue).

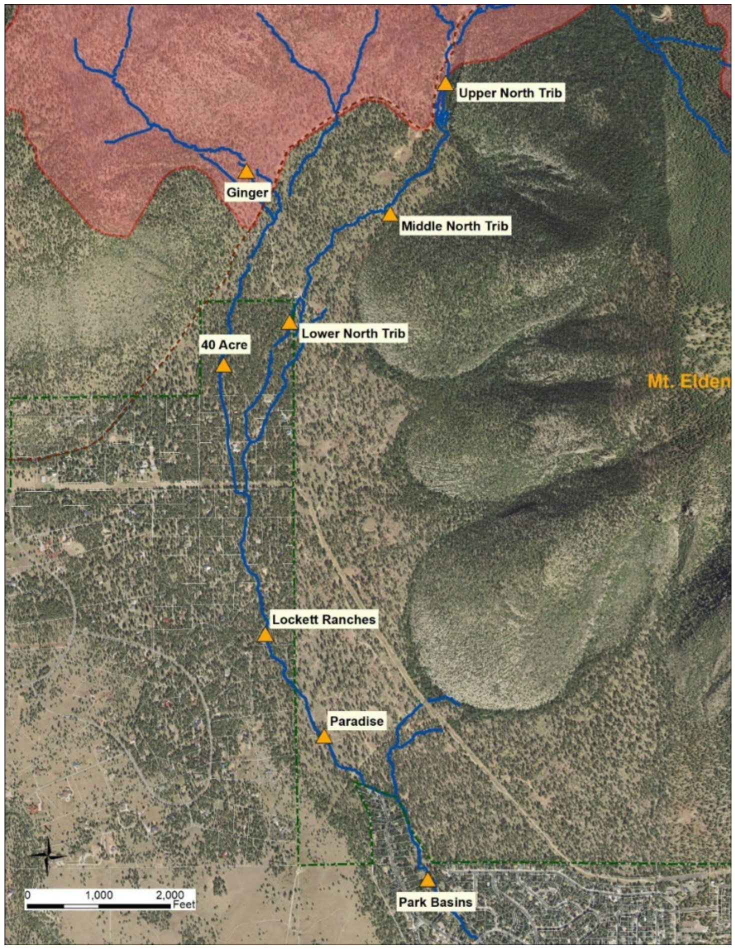

Figure 3. Proposed work areas modeled in FLOWSED/POWERSED. All proposed sites were constructed in 2022 with the exception of Park Basins (planned in 2023).

Results

Channel Conditions

Approximately 20% of the channels in the Museum Fire watershed are incised "G" type channels with high sediment contribution from channel and bank processes. G channels were found primarily in the burned, steep, upper reaches of the watershed; however, some were found in reactivated alluvial fans. Bank erosion from this type of channel can be an order of magnitude higher sediment contribution from bank and channel processes than other non-incised steep slope channels (Rosgen 2002). Aggrading "D" type channels or valleys that can support aggrading channels are roughly 15% of the watershed. While these channels have the potential to store large amounts of sediment, many are gullied and now function as sediment sources rather than sediment sinks. The Rosgen channel type was determined visually during the BEHI surveys, and the results are shown in Figure 4.

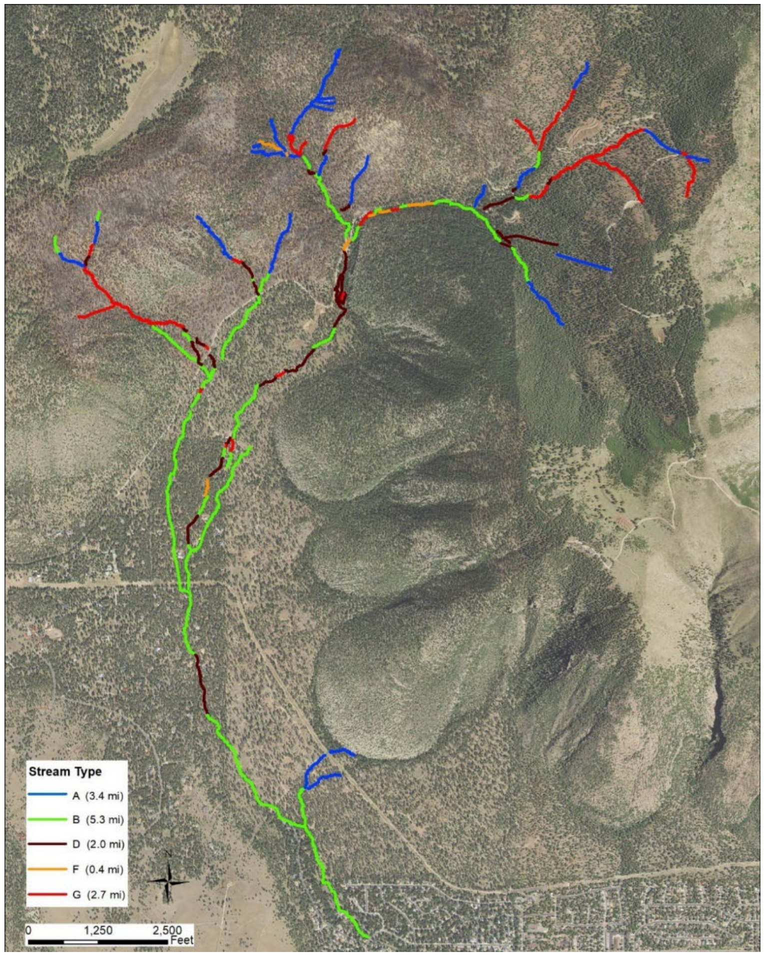

Figure 4. Spruce Wash channel types based on the Rosgen classification systems. "A" and "B" types are generally stable with low sediment contribution. "F" and "G" channel types are generally unstable and are sediment sources, "D" channel types tend to be aggradational.

Sediment Yield

Channel and Hillslope (ERMiT) Sediment Yield

The BANCS model estimates a total sediment yield of 10, 400 tons per year from streambank erosion while the ERMiT model estimates that hillslope erosion would yield 7,000 tons of sediment in 2022. Combinign both methods, sediment yield resulted in a cumulative 17,300 tons per year of predicted sediment yield from channels and hillslopes in their current conditions for the year 2022 (3 years post-fire; Table 1 and Figure 5). Empirical observations by CoF staff were 11,700 tons of sediment delivered to the downstream end of the study site in 2021 from four flood events, the majority of the sediment removed was during the first flood event, despite the magnitude of the flood event being less than some subsequent floods (Schenk et al. 2023).

The BANCS model also calculates the unit bank erosion rate which is the erosion rate per foot of channel. Figure 6 presents the unit bank erosion rate for channels in the Spruce Wash watershed, indicating the channels with the highest expected erosion rates. The Ginger and Wasabi sub-watersheds, which are two steep watersheds in the burn area, have the highest unit bank erosion rates. The results of the ERMiT model showing the predicted hillslope erosion rates are presented in Figure 7 which generally show the highest hillslope erosion rates in the steeper, burned areas of the watershed.

Table 1. BANCS, ERMiT, and total sediment yield for Spruce Wash sub-watersheds. BANCS modeled bank erosion is a result of a channel survey of current condition while hillslope erosion is determined as a year 3 post-fire ERMiT modeled sediment yield. Bold numbers indicate sub-watersheds where hillslope erosion is predicted to be larger than bank erosion. Values are provided as shown in the model output, precision is likely to the hundredths place.

Sub-Watershed	Bank Erosion (tons/year)	Hillslope Erosion in 2022 (tons/year)		Total Bank & Hillslope Erosion (tons/year)
Brookbank	1109	**2190**		3299
Ginger	2943	1270		4213
Lower North Tributary	721	3		724
Lower West Tributary	361	1		362
Oldham	349	267		616
Red Onion	591	**1086**		1677
Spruce	400	4		404
Upper North Tributary	351	334		685
Upper West Tributary	507	**668**		1175
Wasabi	3039	1133		4172
TOTAL	**10,373**	**6,956**		**17,329**

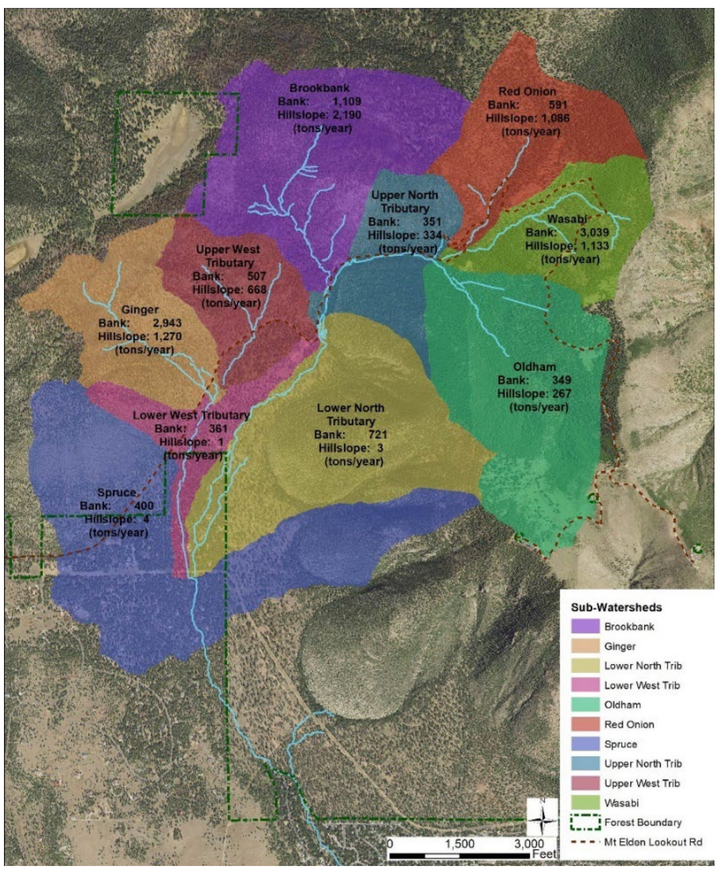

Figure 5. Total sediment yield for the Museum Fire burn scar for sub-tributaries to Spruce Wash, based on WARSSS modeling.

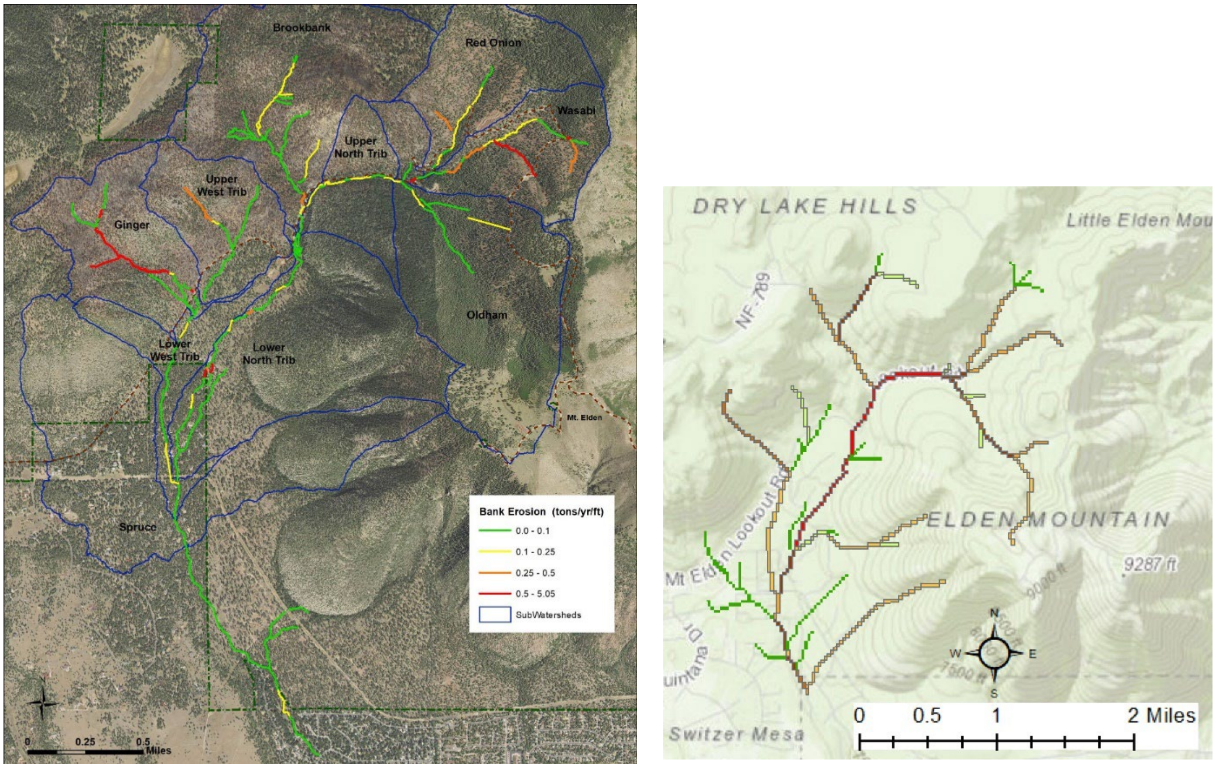

Figure 6. Left: BANCS modeled bank erosion rates for major channels within the Spruce Wash watershed. Right: WEPP modeled bank erosion, there is a similar spatial pattern for "Ginger", "Brookbank", and the unnamed tributary south of "Wasabi", differences exist for the main-stem channel erosion prediction. Shading on the right figure is not to scale with the shading on the left figure.

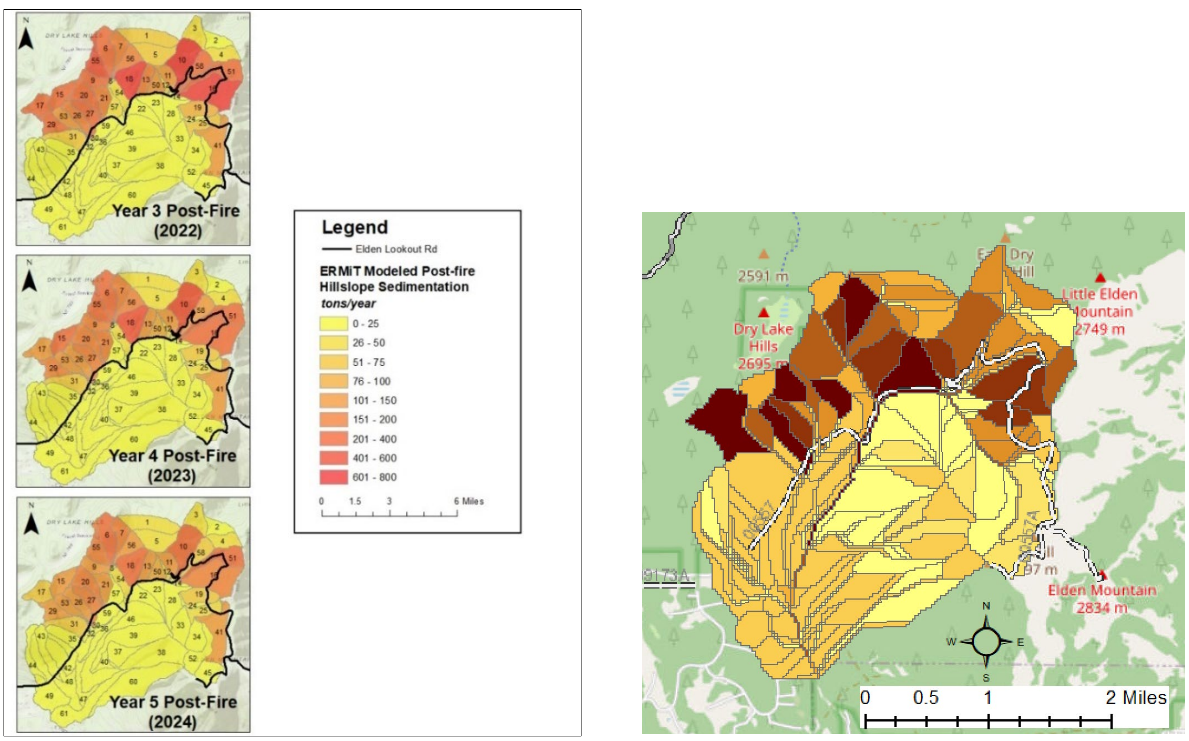

Figure 7. Modeled hillslope erosion rates for 2022, 2023, and 2024 (Left; ERMiT model) and 100 year forecasted annual hillslope annual yield (Right; WEPP model). The WEPP model shading is relative and not to scale with the ERMiT model.

Hillslope (MUSLE) Sediment Yield

The MUSLE model also estimates high rates of hillslope erosion for the three modeled precipitation events. The sub-tributaries utilized for the analysis are the same as those utilized for the average annual sediment transport estimates from FlowSed PowerSed analysis. The results vary widely depending on the precipitation event utilized and the erodibility factor (K) of the soils. Based on field observations, the medium K value likely represents the best estimate of aggregate soil conditions in the various watersheds within the burn area (Table 2).

Table 2. MUSLE model results for soil losses for three different soil erodibility factors (K) for three different rain events (1,2,3") in one hour. The medium K value (0.545) is the most likely approximator for the 2019 Museum Fire.

	Soil Loss with low K value			Soil Loss with medium K value			Soil Loss with high K value		
Sub-Watershed (WS) Name	1"	2"	3"	1"	2"	3"	1"	2"	3"
	tons	tons	tons	tons	tons	tons	tons	tons	tons
Ginger	203.8	814.5	1604.0	383.1	1530.6	3014.3	562.3	2246.8	4424.7
40 Acre	219.0	1162.9	3094.1	411.5	2185.5	5814.7	604.0	3208.0	8535.4
Upper North Trib - Wasabi	368.8	2059.2	4632.7	693.2	3869.8	8706.2	1017.5	5680.4	12779.8
Upper North Trib - Brookbank	664.8	3241.8	7311.4	1249.4	6092.4	13740.3	1833.9	8943.0	20169.3
Middle North Trib	413.5	2156.5	4991.9	777.2	4052.7	9381.3	1140.8	5949.0	13770.7
Lower North Trib	215.9	922.5	1541.5	405.7	1733.7	2896.9	595.5	2544.9	4252.3
Lockett Ranches	404.4	2510.5	6385.7	759.9	4717.9	12000.7	1115.5	6925.4	17615.7
Paradise	217.3	1503.6	3964.4	408.4	2825.6	7450.3	599.4	4147.7	10936.3
Park Basins	211.9	1722.7	4708.7	398.2	3237.6	8849.1	584.5	4752.4	12989.6

Likely the best approximator for Museum Fire

A simplification of the 2021 rain events would provide a MUSLE sediment yield estimate of 5400 tons (three 1 inch rain events in July and one 2 inch rain event in August; all medium K values). Empirical results from in-city sediment removal, as measured at the Cinder Hills Landfill, are provided in Figure 8.

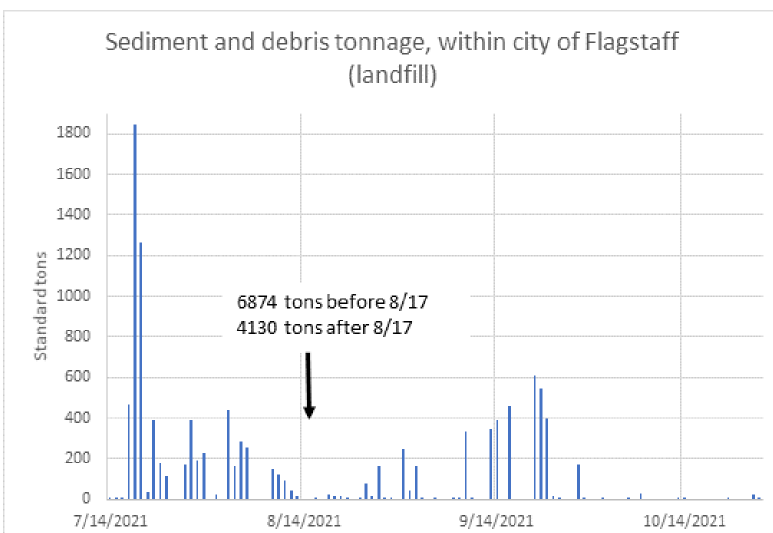

Figure 8. Sediment and debris tonnage removed from channels and streets. Flood events occurred on July 13, 14, 16, and August 17th. Flood flows were predicted at the upstream entry to the CoF as 700, 700, 1000, and 1580 CFS respectively.

Sediment Transport and Retention

FLOWSED/POWERSED modeling determined that five of the seven work area channel cross sections currently pass more sediment than is supplied to them, potentially leading to up-gradient headcutting and continued erosion (highlighted in red in Table 3). The work area cross sections consist of an upstream, single thread "feeder" channel and a degraded, multithread "fan" channel downstream. These five proposed work area cross-sections pass sediment more efficiently than the upstream sediment source cross section due to channel geometry, generally due to a headcut working into a "D" channel and converting it into a "G" channel. Once this process has begun, it exacerbates headcutting and fan degradation, channel migration, bank erosion, and provides little-to-no sediment aggradation (retention or deposition) on the now disconnected alluvial fan. Without direct intervention, these fans and channels will continue to efficiently transport sediment downstream towards the residential areas.

The FLOWSED/POWERSED model was used to estimate the effect of rebuilding alluvial fans and channel stabilization techniques and to determine areas to increase sediment retention within each project. At each work area, a conceptual design cross-section was used and evaluated for its efficiency in sediment transport. Design cross sections consist of a restored fan feature with the eroded, defined flow paths graded flat. Results indicate that design cross-sections retain an average of 70% more sediment in proposed work areas than the alluvial fans and channels in their current (fall 2021) condition (Table 3). This added sediment retention was accomplished by widening and repairing the existing channel into a designed alluvial fan channel to fill the valley bottom. This reduces the ability of the channel to transport sediment by lowering shear stress which is a function of slope and depth. The slope of the channel remains the same, but the depth is lowered by allowing for a wider flow path. The modeled 70% reduction removes all but 3,440 tons of sediment on an average annual basis per this analysis. It should be noted that large, single events are not modeled by this analysis and could potentially deliver more sediment. Flow events in 2022 were muted in Spruce Wash due to small rain events, the alluvial fan sites that were constructed prior to monsoon season did appear to function well in terms of sediment aggradation and attenuation (Figure 9). Observations on the nearby Pipeline Fire burn scar showed consistent sedimentation in the 70 to 80% range, based on repeat surveys and sediment haul off (Tiffany Construction LLC and Coconino County Flood Control District personal communications).

Table 3. FLOWSED/POWERSED model results indicating potential sediment retention for proposed sediment basins. Columns marked in red are net erosional alluvial fans in the current (2021) condition, green indicates net aggradation (sediment storage).

Potential Work Area Name (*Figure 5*)	**Incoming** Transport Capacity	**Current** Channel Transport Capacity	**Design** Channel Transport Capacity	Difference between **Incoming** and **Current** Transport Capacity	Difference between **Incoming** and **Design** Transport Capacity	Sediment Retention at Proposed **Design** Channel	Percent Sediment Retained by **Design** Channel
-	(tons/ year)	(tons/ year)	(tons/ year)	(tons/year)	(tons/year)	(tons/year)	%
-	**A**	**B**	**C**	**D**	**E**	**F**	**G**
-	-	-	-	= A - B	= A - C	= E - D	= (1-C/A)*100
Ginger	416	357	59	59	357	298	86
40 Acre	1093	1462	297	-369	796	1165	73
Upper North Trib	586	3368	237	-2782	349	3131	60
Middle North Trib	1243	1502	440	-259	803	1062	65
Lower North Trib	1422	2581	486	-1159	936	2095	66
Lockett Ranches	2000	1572	840	428	1160	732	58
Paradise	2236	5101	496	-2865	1740	4605	78

Figure 9. Ginger alluvial fan work site (looking upstream) during a 2022 flow event, note the spread of flow and subsequent drop in water velocity allowing sediment aggradation.

The commonly used WEPP model (for US Forest Service projects) demonstrated much lower sediment yields (4300 tons/year) than the WARSSS model (17,000 tons/year) and empirical results (11,000 tons/year in 2021) for the Museum Fire burn scar and Spruce Wash watershed and slightly less than the event based MUSLE model (5400 tons/year). The reasons for this are not completely known at this time but are likely partly due to the long period of watershed complacency in the San Francisco Volcanic Field (estimated at several thousand years; Stempniewicz 2014; Fulé et al. 2023) leading to abnormally large amounts of stored hillslope and channel sediment at risk of transport after drought fueled catastrophic wildfires. The large antecedent sediment storage volume is not accounted for in WEPP or MUSLE and only partly accounted for in WARSSS through the empirical measurements used to inform BANCS. Other factors likely include uncertainty in the empirical estimates (both over-estimating due to water volume in the sediment/debris loads as well as under-estimation due to floodplain areas not addressed by flood cleanup efforts), as well as WEPP model limitations for rill and gully erosion processes (hillslope incision). Hillslope gullying is one of the most prevalent forms of erosion in Arizona post-wildfire environments making the estimation of their sediment yield vitally important (Neary et al. 2012).

Conclusions

As evidenced by flooding events in 2021, sediment supply from the burn area is quite high with an observed rate of greater than 11,000 tons into the neighborhoods in 2021 alone. The WEPP model appears to underestimate sediment delivery by roughly 50% based on empirical observations and the modeled results from the WARSSS suite of models and to a lesser extent the event driven MUSLE model, possibly due to the inability of WEPP to account for gully incision. However, the advantage of WEPP, over WARSSS, is its ease of use and easy learning curve. All three modeling domains, MUSLE, WEPP, and WARSSS showed drastic increases in channel and hillslope sediment yields post-fire.

Poor channel condition as well as hillslope conditions provide a very high sediment contribution to the downstream channel and floodplain. The majority of high erosion areas are located high in the watershed. Steep slopes and lack of accessibility likely preclude active restoration of these channels or any hill slope activities other than revegetation by hand labor. The nature of the channels (mostly G and F "Rosgen" type channels) indicate that the channel form is in the early stages of evolving to a stable form. Formation of a small floodplain and reasonably stable channel side slopes (2H:1V minimum) will require the erosion of significant amounts of sediment. The process will likely take years to decades, before relative stability has been reached. As such, there is a high potential for greater than normal sediment loading for the foreseeable future and elevated life and safety risk to the community.

Several sub-watersheds were identified that exhibited higher hillslope erosion rates than adjacent channels. Initial post-wildfire sediment studies found that channel processes are generally larger sources of erosion, though that narrative is rapidly changing with more case studies and better landscape scale surveying and monitoring (Rengers et al. 2016). The poor hillslope conditions are cause for concern if they do not begin to improve soon as high sediment loads from hills slopes will generally contribute to further degradation of the receiving channel. Two consecutive years of drought likely contribute to this condition, however continued erosion and rilling hinder seed establishment further retarding recovery. These areas should be monitored over the next few growing seasons and may need intervention in order to recover. The sediment transport models indicate a high potential for successful reduction in sediment as flows cross restored alluvial fan areas, this was proven in 2022 where observations at the nearby Pipeline Fire indicate a sediment retention greater than 70% on the completed alluvial fan projects within those watersheds. Models suggest that restored fan surfaces can reduce sediment transport across the fan features by up to 70%. Some fan areas (especially the West Tributary or Ginger) have the potential to not only reduce sediment transport but also sediment contribution from bank erosion. Current high bank erosion rates can be eliminated by eliminating the current gullied channel and restoring the fan function. Fan areas on the main channel of Spruce Wash which already store some sediment can be greatly improved by grading to restore the consistent fan feature.

Care should be taken to ensure that alluvial fan surfaces are as large as possible to provide many years of sediment storage without concentration of flow. Given that the potential for sediment transport to the fan areas is high and likely a long-term consequence of post fire flooding. Fan areas should be extended as much as possible to provide a maximum useful life to the feature. Additionally, the small fan areas and high sediment loads suggest that some areas may require maintenance to prevent accumulated sediment from directing flows to sensitive areas, this was observed in the northern portion of the Pipeline Fire burn scar in 2022 as sediment loads overwhelmed the existing alluvial fan project built to the smaller 2010 Schultz Fire footprint.

Sediment output from the restored fans appears to be moderate over a long-term average. However, the relatively steep fans will produce higher shear stresses at high, infrequent flows. For example, peak discharges modeled for a 2" per hour precipitation event over the whole watershed (~1300 CFS) produce enough shear stress on the Paradise fan to move ten inch diameter sediment. Consequently, these infrequent precipitation scenarios will have the potential to move large quantities of material through the fan system, even though most is retained on the fan.

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