Post-wildfire sediment source and transport modeling, empirical observations, and applied mitigation: an Arizona USA case study

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Abstract

Post-wildfire floods are receiving greater attention as wildland-urban interfaces become more common and as catastrophic wildfires have increased in frequency. Sediment sourcing, transport, and deposition in the post-wildfire environment receive attention due to the severity of risk caused by debris flows and concentrated sediment flood flows. This study provides a series of sediment model predictions based on MUSLE and the WARSSS suite of models that included: ERMIT, BANCS, and FLOWSED/POWERSED for the 2019 Museum Fire (809 Ha of steep slope *Pinus ponderosa* forest on a series of basaltic domes). A comparison is provided for the internet-based WEPPcloud post-wildfire sediment model. Empirical evidence from four floods in 2021 indicated 9,900 Mg of sediment yield to city of Flagstaff neighborhoods, the WEPP model estimated 3870 Mg/year, MUSLE predicted 4860 Mg/year (based on the four events), and the WARSSS suite of models predicted 4630 Mg/year. Both WEPP and WARSSS estimated more sediment yield from channels than hillslope (51%/49% and 60%/40% respectively) though the spatial patterns differ between the models. Sediment mitigation structures, or "work areas", are discussed as real-world applications of sediment forecasting for reducing downstream impacts. Continued revisions of sediment forecasts, based on case studies such as this one, can provide managers and policy makers with tools for risk mitigation and emergency management.

1. Introduction

Post wildfire flooding at the wildland-urban interface (WUI) is an increasingly important issue for the health and safety of millions of humans living in or adjacent to semi-arid forests. 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 (Sankey et al. 2017). 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 sediment transport and floods following a fire to prevent or lessen impacts to safety and property damage. A key portion of this process is understanding the potential for damaging debris flows and sediment sourcing, transport, and aggradation (Ebel et al. 2023). The sediment component of the post-wildfire flood paradigm is perhaps the most damaging due to physical impacts (e.g. damage to infrastructure), bulking factors to flood flow volume, and long-term damage to soil profiles and stream channels that hamper watershed ecosystem recovery (e.g. Moody et al. 2013; Neary et al. 2011; Shakesby 2011).

In the past two decades there has been an emphasis on predicting, and remediating, post-wildfire sediment sourcing and transport (Shakesby et al. 2016; Ebel et al. 2023). Most studies have been focused on hillslope and channel process and determining accurate, or precise, estimates of sediment fluxes (East et al. 2021; Rengers et al. 2021; Wu et al. 2021; Ebel et al. 2023). While many studies rely on empirical measurements there has been recent improvements and updates to post-wildfire sediment modeling. These improvements allow for rapid, relatively inexpensive, assessments post-wildfire but potentially at the cost of precision or accuracy (Lopes et al. 2021; Ebel et al. 2023).

This study explains sediment prediction methodologies utilized for a relatively small fire in Flagstaff, Arizona USA to predict sediment quantities as well as flow paths and sedimentation areas for the Museum Fire (2019). These methods have successfully guided mitigation efforts for the nearby Schultz Fire (2010; Neary et al. 2012) and were also used in another nearby fire in 2022 (Pipeline Fire). Three models were compared to empirical observations to provide an estimate of model precision and accuracy, the Watershed Assessment of River Stability and Sediment Analysis (WARSSS), Modified Universal Soil Loss Equation (MUSLE), and the Watershed Erosion Prediction Project (WEPP), all three were then compared to field observations at the downstream urban environment.

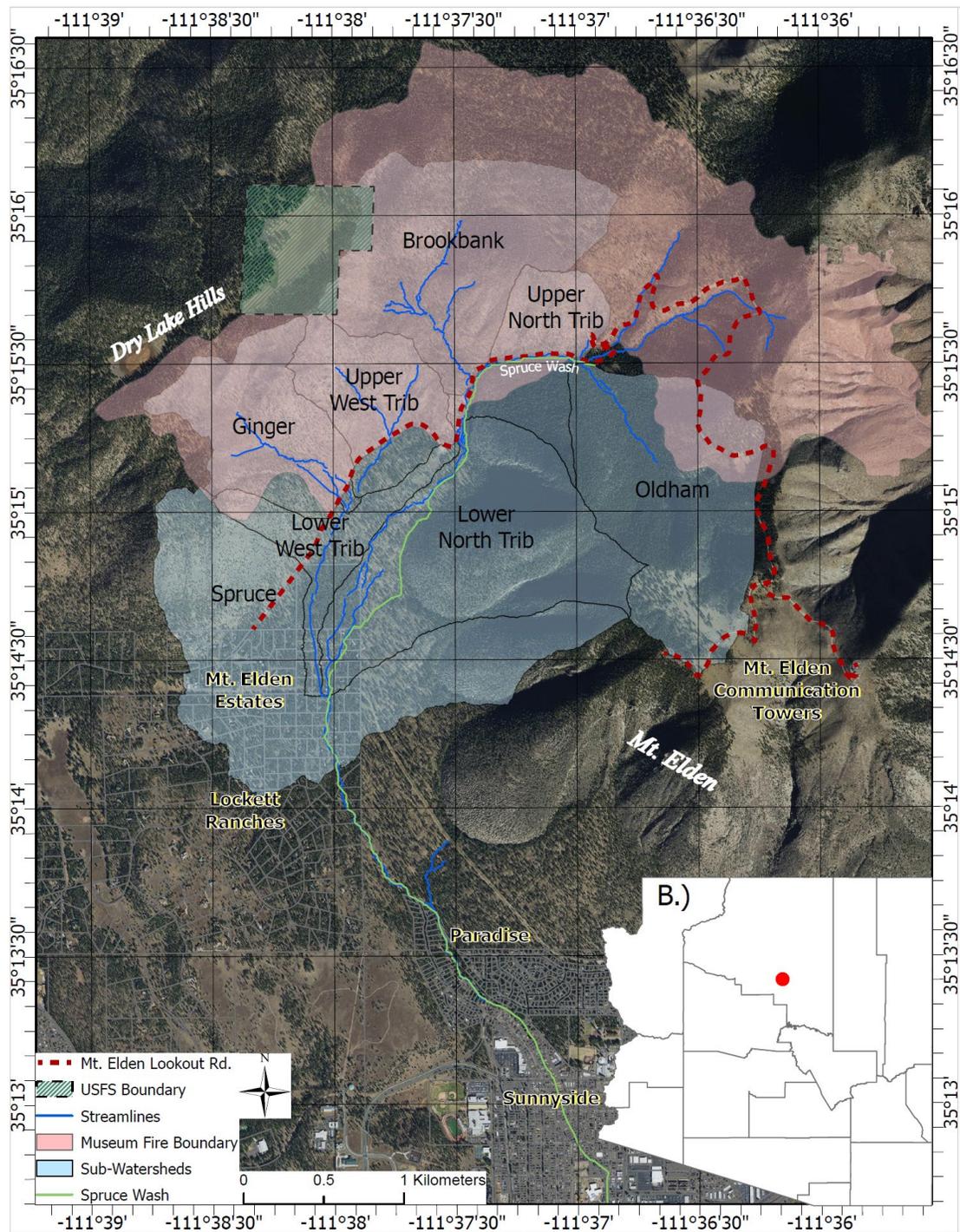
Additionally specific mitigation areas are discussed at the end of this study and are described as "work areas". These work areas include alluvial fan restorations that spread flow allowing for a drop in stream power. The loss in stream power allows for sediment accretion upstream of urban neighborhoods (Beers et al. 2023). The objective of this study is to provide an estimate of the precision and accuracy of three sediment modeling techniques (WARSSS, MUSLE, and WEPP) and determine where future modeling improvements should be focused upon. A secondary objective is to display the utility of post-wildfire sediment modeling for determining the location, and type, of sediment mitigation structures.

2. 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 (Quisenberry 2009; 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 (2695 m) as well as the western portion of Mount Elden (2835 m), a larger protuberance of the same orogeny (Holm 2019; Schenk et al. 2021). A previous USGS study observed a peak flow of 0.14 cubic meters per second in the Spruce Wash watershed over a period of 11 years (Hill et al. 1988) despite a watershed contributing area of greater than 1450 hectares.

The Museum Fire occurred in July 2019 over 800 hectares 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; 2160 m) is a rural residential area and is the uppermost residential area within the Spruce Wash Watershed. Approximately one and half kilometers downstream and separated by open U.S. Forest Service (USFS) land are the urban residential areas of Paradise/Sunnyside (2120 m), 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-wildfire, previously complacent; Fulé et al. 2023). Paradise/Sunnyside are on the toe of inactive alluvial fans and adjacent to the broad, ephemeral, and formerly un-channelized 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, pre-fire surface water flows within the channels were primarily from stormwater runoff during normal precipitation events from local CoF streets (Schenk et al. 2021; Schiefer and Schenk, 2024).

2.1 Flood Events

The Flagstaff region saw record low summer monsoonal rain in 2019 and 2020 with no substantial post-wildfire 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; Porter et al. 2023; Schenk et al. 2023; Sankey et al. 2024). Post-wildfire flooding resulted in vast amounts of sedimentation in downstream residential areas as existing drainage features and channels were overwhelmed with sediment and debris (e.g. https://www.weather.gov/fgz/FlagstaffJuly2021). These flood events allowed for empirical comparisons to the modeled predictions.

 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 and shown on the lower portion of this figure. Background aerial imagery is public domain (Coconino County 2015).

3. Methods

3.1 Flood Flow Modeling

Post-wildfire flood modeling was completed in August 2019 and was based on a 2-D hydrologic-hydraulic numerical model created in FLO-2D (JE Fuller 2019; JE Fuller 2022). Initial flood modeling was completed at a 20-foot (6m) grid scale using 2015 lidar elevation data, subsequent modeling was

completed at a 5 foot (1.8m) grid scale using a fall 2019 lidar elevation dataset, both datasets are available on the United States Geological Survey National Map portal (https://www.usgs.gov/programs/national-geospatial-program/national-map). All modeling indicates an approximate 10 to 100 times (one to two orders of magnitude) increase in surface water runoff depending on rain event; more information on hydrologic conditions is provided in a conference proceedings paper (Schenk et al. 2023).

3.2 Sediment Modeling

Sediment modeling focused on quantifying relative sediment sources relating to channel and hillslope erosional processes. The Spruce Wash watershed within the Museum Fire burn scar was divided into sub-watersheds, based on tributaries in the USGS National Hydrography Dataset, to identify high-sediment yield areas (USGS 2019). Areas downstream from high sediment yield areas were identified as "work areas" for applied sediment control practices that have the greatest impact on limiting downstream sediment transport.

The WARSSS model (Rosgen 2009), was the first modeling suite used for this fire (in 2021 post-flooding) due to its successful sediment transport predictions after the nearby 2010 Schultz Fire (NCD 2012, Neary et al. 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. An annual average sediment yield is used due to the highly heterogenous precipitation distribution in the American Southwest during monsoon storms. This annual average sediment yield, therefore, is appropriate 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 (Rosgen 2009). 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 and Benhardt 1977) is utilized to estimate sediment supply from hillslopes during specific precipitation events. Discharges 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-wildfire 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-wildfire 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; Hall and Bledsoe 2023). 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 (Rosgen 2006; Hall and Bledsoe 2023). These data are difficult to obtain for ungauged ephemeral systems; we used 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).

Once high-sediment yield areas are identified, sediment transport analyses are conducted at typical channel cross-sections that typify the range of channel conditions from upstream to 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 (a hypothetical 2% slope post-restoration) was used to understand the feasibility of altering the downstream sediment delivery and was based on the upstream sediment supply.

3.3 Assessing the geomorphic channel condition

3.3.1. *BEHI data collection*- Bank erosion hazard index (BEHI) surveys were used to qualitatively evaluate all eroding channels within the Spruce Wash watershed, (Rosgen 2009; Figure 2). Collected data consisted of channel bank height, channel and bank material, length of channel, vegetation and root density, bank slope angle, valley and stream type classification (Rosgen 1996), and near bank stress (NBS).

Figure 2. Surveyors performing a BEHI analysis on a typical channel along Spruce Wash. Photo taken in fall 2021 approximately 500 m upstream of Mount Elden Estates.

3.3.2. *Channel Surveys*- channel cross-sectional 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 (Figure 3), longitudinal channel profiles, and pebble counts were completed to evaluate the channel slope and characteristics of specific channel reaches.

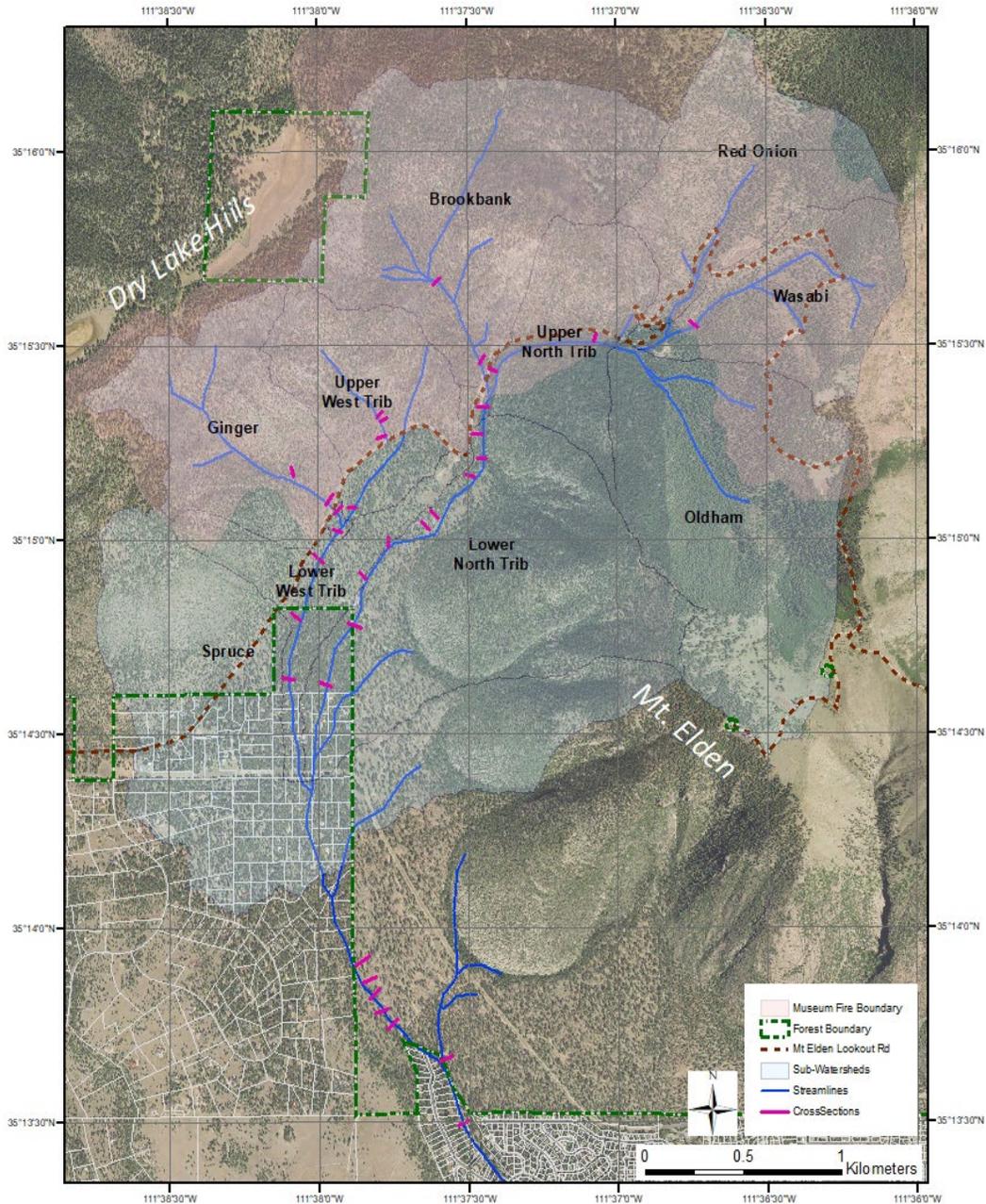



Figure 3. Cross sections within the Spruce Wash watershed, the 2019 Museum Fire burn area is shown in light red. Background aerial imagery is public domain (Coconino County 2015).

3.4 Estimating Sediment Yield

3.4.1 Channel Sediment Yield- The Bank Assessment for Non-point source Consequences of Sediment (BANCS) model was used to estimate annual sediment yield (Rosgen 2009). The BANCS model utilizes BEHI and NBS survey data to estimate sediment supply from channel bank sources and yields a sediment supply in mass 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 Mg/year/longitudinal meter for all evaluated reaches.

195 3.4.2 Hillslope Sediment Yield- The Erosion Risk Management Tool (ERMiT) and Modified Universal Soil Loss Equation (MUSLE) model were used to estimate hillslope sediment yield. The ERMiT model predicts sediment yield annually while the MUSLE model is based on precipitation events (storm-based).

The ERMiT models uses soil burn severity, vegetation type, rock content, hillslope gradient, soil type,
200 hillslope length, and annual precipitation to model sediment yield (Mg/year) up to five years post fire (Robichaud et al. 2007). For the scope of this analysis, 2021 was used as the second-year post-wildfire. Therefore, only years 3 (2022), 4 (2023), and 5 (2024) sediment yield were modeled. To capture the variability in hillslope impacts, the Spruce Wash watershed was subdivided into sub-catchments using watershed delineation in ESRI ArcMap. Each catchment was evaluated individually for its sediment
205 yield.

The MUSLE is based on the Universal Soil Loss Equation (USLE) but utilizes transport efficiency and soil erodibility (Igwe et al.2017). For the post-wildfire watersheds, the MUSLE model is useful for modeling post-wildfire sediment yield because soil erodibility increases due to hydrophobic, ash laden soils, and transport efficiency increases due to increased runoff from decreased infiltration and
210 retention. The MUSLE model input for post-wildfire situations requires instantaneous peak discharge and total volume of 1", 2" and 3" (2.5, 5, and 7.5 cm respectively) precipitation in one hour events in addition to watershed area, slope, and soil erodibility. Unlike the ERMiT model, the MUSLE model predicts event-based sediment yield in mass per event. Soil erodibility (K values) were estimated for low, medium, and high erodibility at 0.29, 0.545, and 0.8 respectively based on field conditions. The
215 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.

3.5 Observed Sediment Transport and Aggradation

Observed sediment transport and aggradation were collected from CoF staff during 2021 flood events
220 (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. Each truck load of flood related sediment was measured for potential Federal and State disaster reimbursement,
225 providing a relatively accurate empirical measure of sediment flux to the ultimate outfall (city of Flagstaff neighborhoods).

3.6 Evaluating Sediment Transport and Retention
FLOWSED/POWERSED, a part of the proprietary RiverMorph software package (Rosgen 2006), was used to model sediment transport through channels in their current condition (2021) and through
230 conceptual redesigned channels for mitigating sediment transport. FLOWSED/POWERSED predicts average annual sediment transport at a stream reach scale based on flow duration curves for the reach, sediment rating curves for discharge, and the stream power at each stage as determined by channel morphology. Modeling is based on a typical channel cross section at a riffle within each reach. Stream power is calculated at stage intervals depending on cross section shape. Flow duration at each stage
235 and sediment transport rates are utilized to estimate total sediment load at each stream stage then summed for a total average annual sediment capacity at each reach.

For this study, dimensionless flow duration curves were derived from data collected at nearby watershed studies in Beaver Creek watersheds (Baker 1982). The dimensionless curves were adjusted using the new estimated 'bankfull' discharge which was derived from runoff models developed for the Museum
240 Fire area (Schenk et al. 2023). The one year return interval precipitation event was used for "bankfull" discharge and approximates the post-wildfire channel forming discharge. Dimensionless sediment rating curves for the project area were derived from sediment rating curves for poor condition watersheds in the Beaver Creek watershed studies (suspended sediment) and poor condition post-wildfire watersheds in Colorado, USA (Rosgen 2010).

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Based on preliminary sediment yield analyses, FLOWSED/POWERSED was modeled at eight proposed work areas. 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 (proposed) design cross-section. The design cross-section informed the final work area cross-section and was drawn in RiverMorph to incorporate a design that promotes the greatest amount of sediment retention.

For each model run, FLOWSED and POWERSED required the following inputs: bankfull cross-sectional area, Manning's n value, bankfull discharge, slope, suspended sediment (mg/L), measured bankfull bedload (lb/s), a flow duration curve, and a sediment rating curve comparison. FLOWSED models the total annual sediment yield, both suspended and bedload, using flow-duration curves and their corresponding sediment yields. The dimensionless flow-duration curve is developed from representative watersheds in the region using USGS stream gage data. The POWERSED model compares sediment transport in various configurations of channel geometry.

The FLOWSED/POWERSED model was used to estimate the effect of rebuilding alluvial fans, and channels, to increase sediment retention upstream of the city. A conceptual design cross-section was used at each work area 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 and stabilized with lateral rock sills. 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 and stream power. The slope of the channel remains the same, but the depth is lowered by allowing for a wider flow path.

WEPP (Watershed Erosion Prediction Project) model runs were completed using the WEPPcloud online toolkit (http://wepp.cloud/weppcloud/) in 2022 to compare with the WARSSS suite of models presented above. WEPP 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-wildfire "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; https://inciweb.nwcg.gov/) 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 the Spruce Wash entry into the CoF neighborhoods (Linda Vista Avenue; 35 13'22.74", 111 37'31.03").

4. Results

4.1 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 (Figure 4). 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 2009). 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.
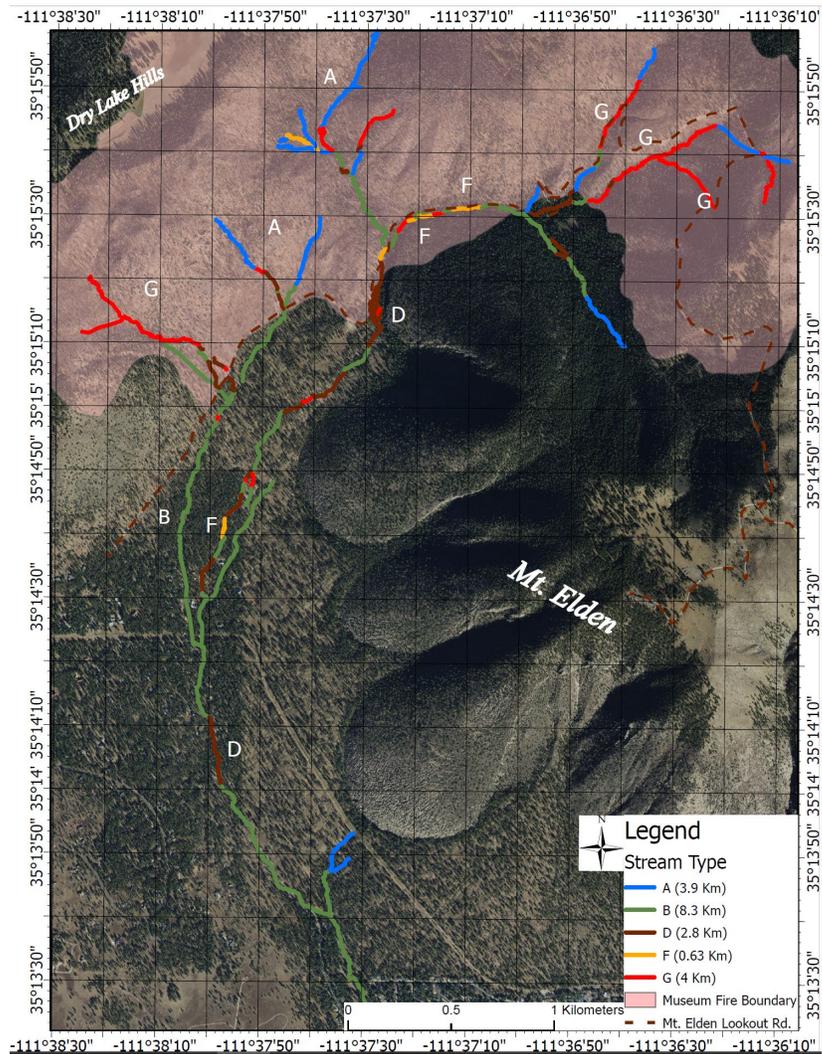
Figure 4. Spruce Wash channel types based on the Rosgen classification systems. "A" and "B" types are generally stable with low sediment contribution. "F" and "G" channel types are generally unstable and are sediment sources, "D" channel types tend to be aggradational (Rosgen 2009). Background aerial imagery is public domain (Coconino County 2015).

4.2 Sediment Yield

4.2.1 *Channel and Hillslope (ERMiT) Sediment Yield*: The BANCS model estimates a total sediment yield of 9,408 Mg/yr from streambank erosion while the ERMiT model estimates that hillslope erosion would yield 6,300 Mg of sediment in 2022. Combining both methods, sediment yield resulted in a cumulative 15,720 Mg/yr of predicted sediment yield from channels and hillslopes in their current conditions for the year 2022 (3 years post-wildfire; Table 1 and Figure 5). However, these channels don't have the capacity to transport the entire sediment source to the city, the POWERSED/FLOWSED models (Figure 5 and 6) take transport capacity into account and indicate a transport rate of 4630 Mg/year on average. Empirical observations by CoF staff were 9,900 Mg of sediment delivered to the downstream end of the study site in 2021 from four flood events, the majority of the sediment transported to the city 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 estimates the unit bank erosion rate which is the erosion rate per longitudinal length of channel (0.3m in this case). Figure 7 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 8 which generally show the highest hillslope erosion rates in the steeper, burned areas of the watershed.

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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-wildfire 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,
320 **precision is likely to the hundredths place.**

Sub-Watershed	Bank Erosion	Hillslope Erosion in 2022	Total Erosion	Area	Total Unit Erosion
	(Mg/year)	(Mg/year)	(Mg/year)	(Hectares)	(Mg/year/hectare)
Brookbank	1006	**1986**	2,992	163	18
Ginger	2670	1152	3,822	87	44
Lower North Tributary	654	3	657	170	4
Lower West Tributary	327	1	328	51	7
Oldham	317	242	559	163	3
Red Onion	536	**985**	1,521	90	17
Spruce	363	4	367	210	2
Upper North Tributary	319	303	622	62	10
Upper West Tributary	460	**606**	1066	69	15
Wasabi	2757	1028	3785	74	51
TOTAL	**9,408**	**6,309**	**15,717**		
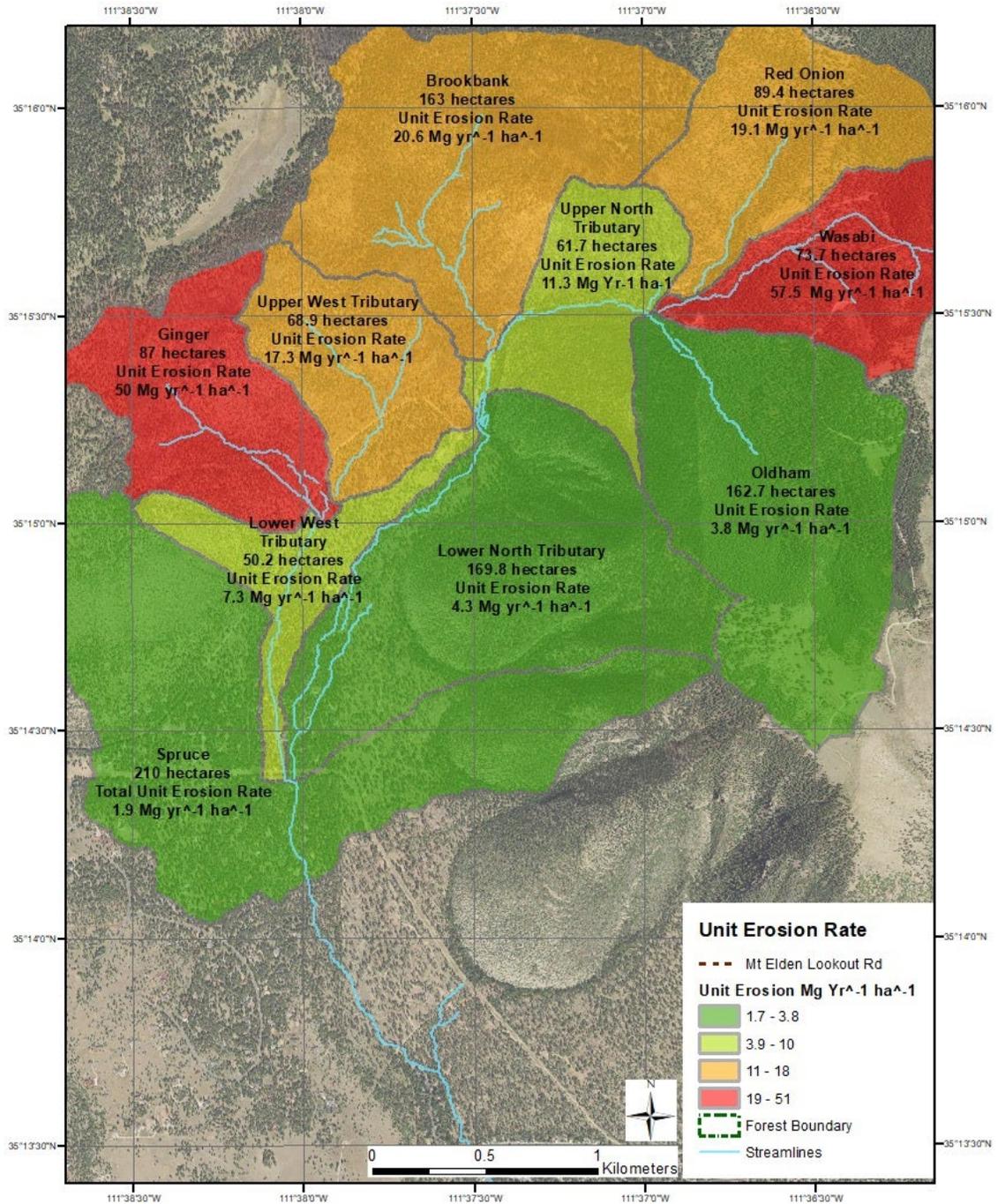
Figure 5. Unit erosion rates for each sub-watershed based on the ERMiT model. Background aerial imagery is public domain (Coconino County 2015).

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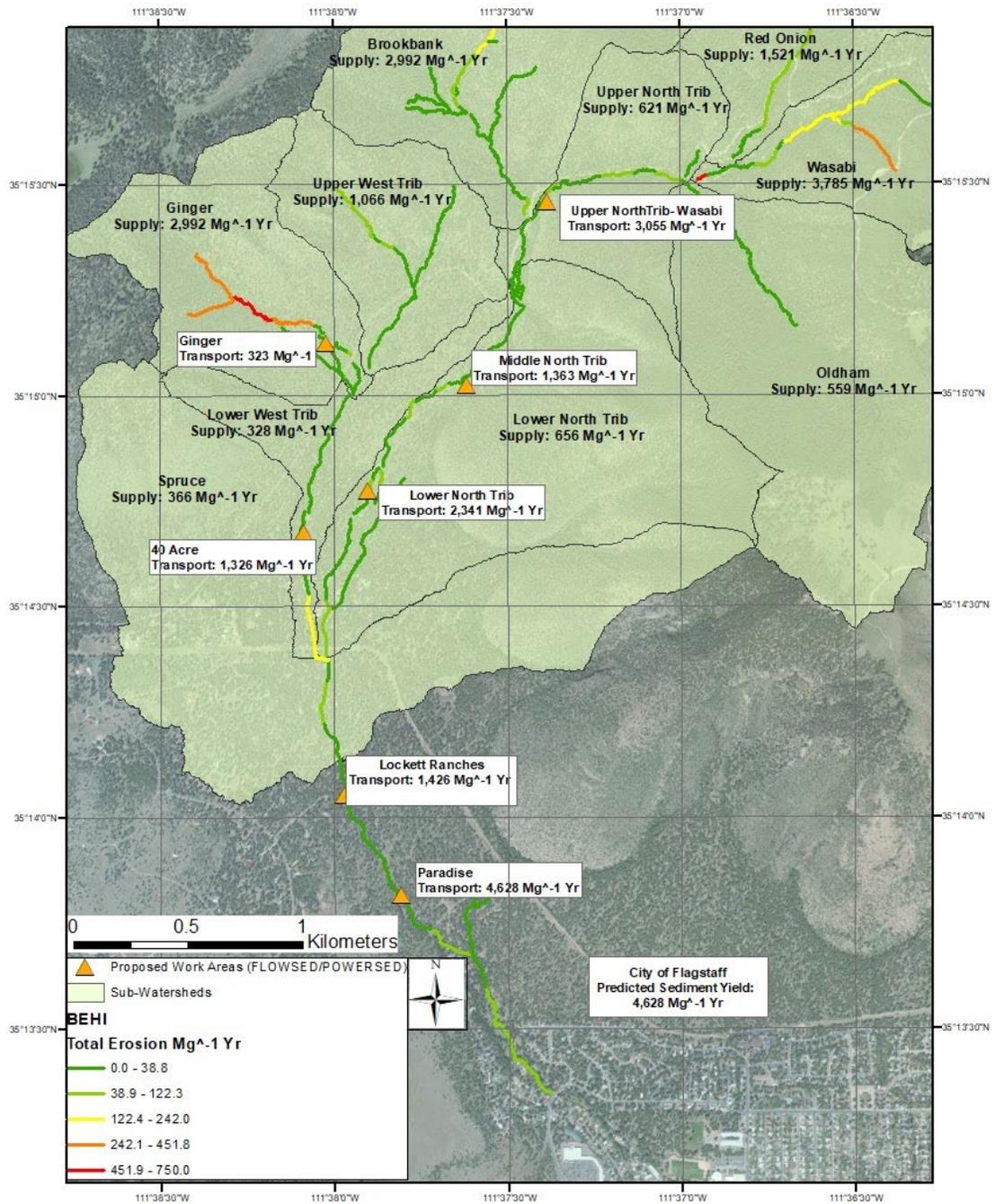
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Figure 6. Sediment transport capacity for all work areas (constructed in 2022 and 2023) from the POWERSED/FLOWSED model. Background aerial imagery is public domain (Coconino County 2015).

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A)   **B)**

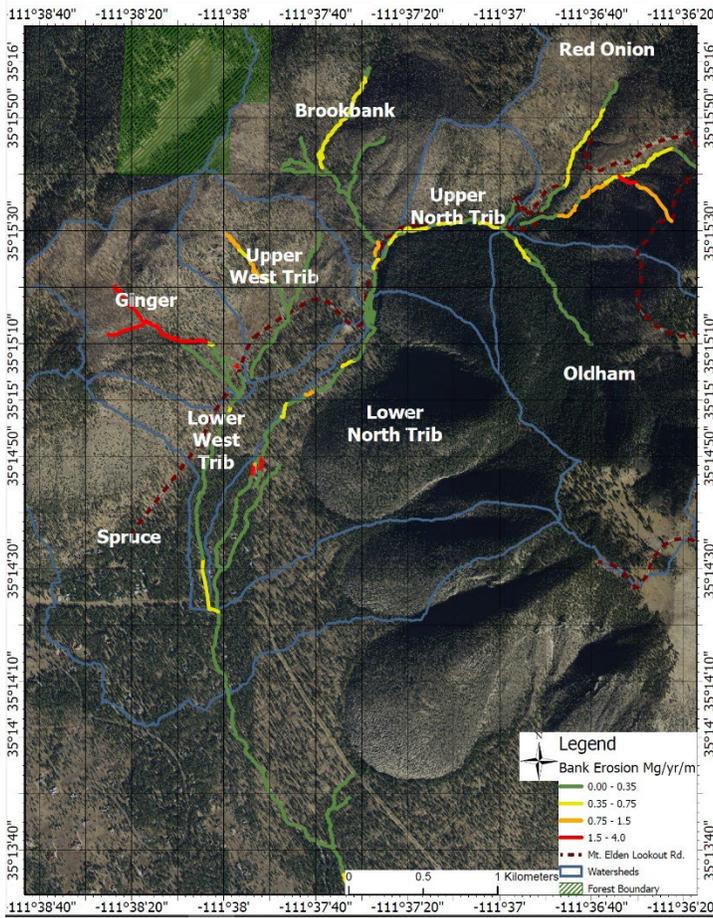
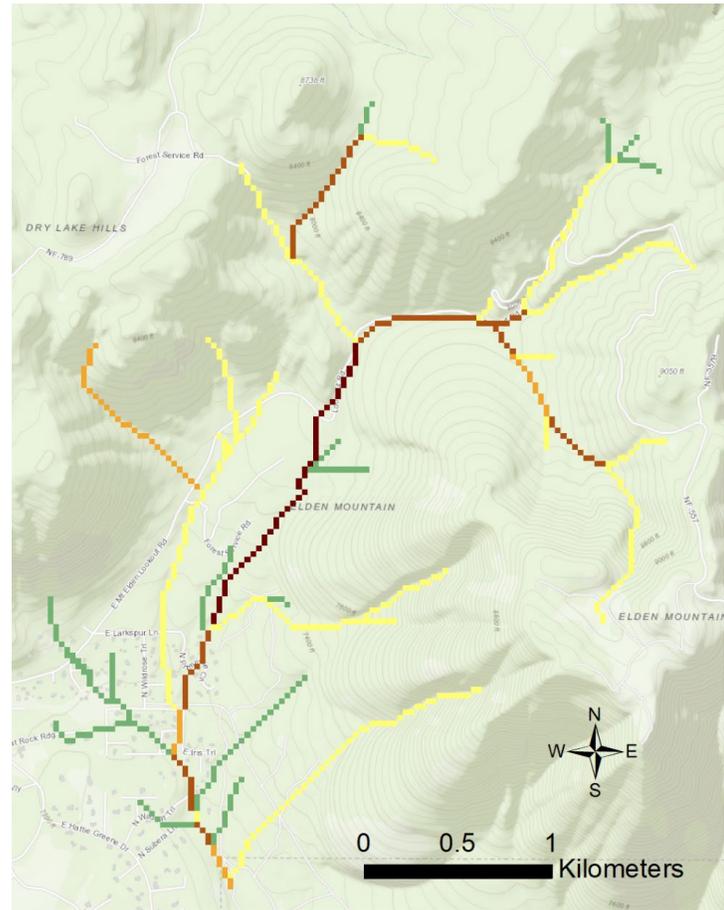
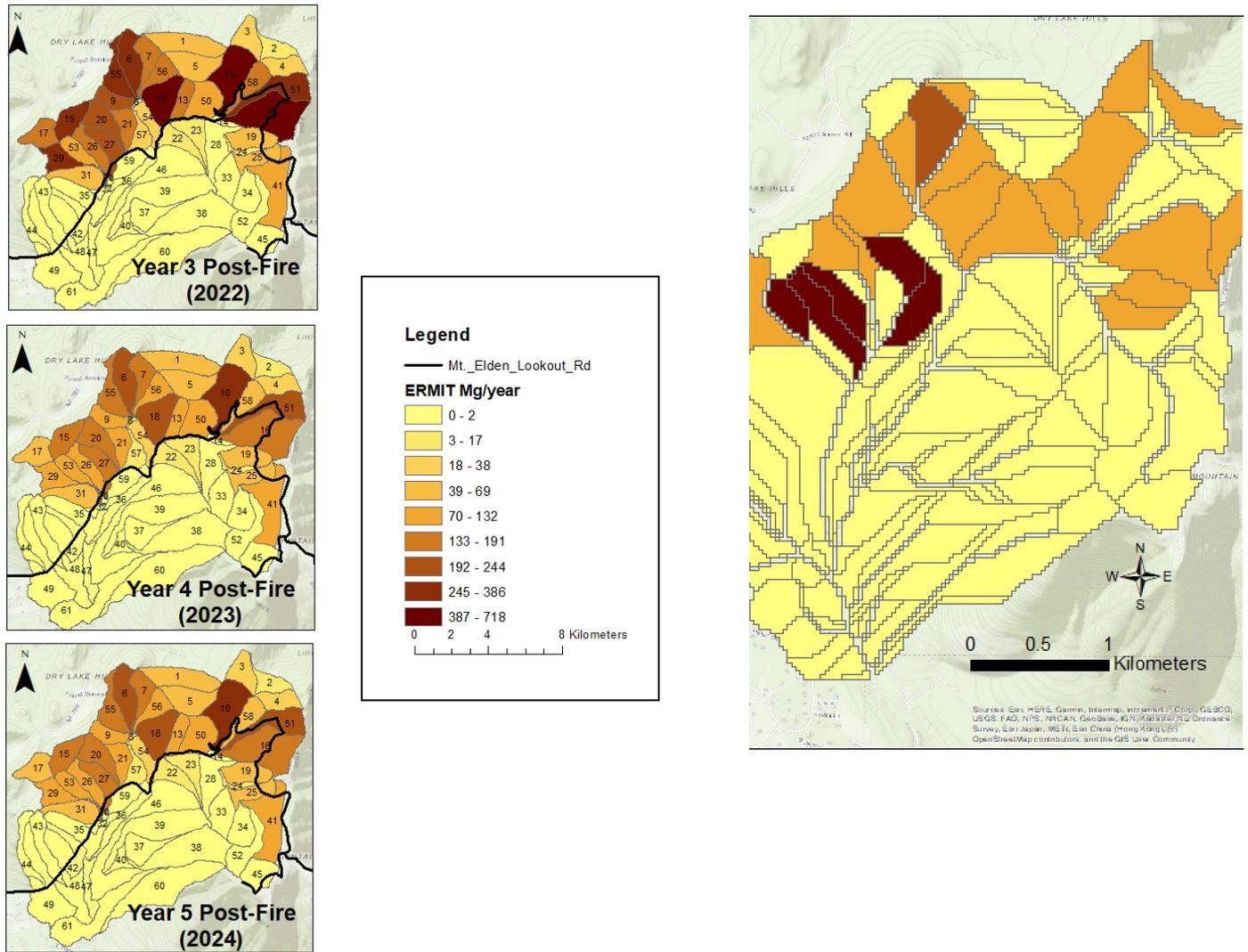



Figure 7. A) BANCS modeled bank erosion rates for tributaries within the Spruce Wash watershed. B) WEPP modeled bank erosion, there is a similar spatial pattern for "Ginger", "Brookbank", and the unnamed tributary south of "Wasabi", differences exist for the main-stem channel erosion prediction.
345 **Background aerial imagery is public domain (Coconino County 2015) for Figure 7a, background imagery for Figure 7b is public domain USGS NLCD data (Homer et al. 2012).**

A)
B)

355   **Figure 8. Modeled hillslope erosion rates for 2022, 2023, and 2024 (A: ERMiT model) and 100 year forecasted annual hillslope annual yield (B: WEPP model). The WEPP model shading is to scale with the ERMiT model. Background imagery is USGS NLCD data in the public domain (Homer et al. 2012).**

4.2.2 Hillslope (MUSLE) Sediment Yield

360   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 (0.545) likely represents the best estimate of aggregate soil conditions in the various
365   watersheds within the burn area (Table 2).

A simplification of the 2021 rain events would provide a MUSLE sediment yield estimate of 4860 Mg, three 1-inch (2.54 cm) rain events in July and one 2 inch (5.08 cm) rain event in August; all medium K values. No other large rain events occurred in 2021 over the Museum Fire burn scar.

370 **Table 2. MUSLE model results for soil losses for three different soil erodibility factors (K) for three different rain events for 1 inch, 2 inch, and 3 inch (2.5, 5, 7.5 cm) in one hour. The medium K value is the most likely approximator for the 2019 Museum Fire. K values included 0.29, 0.545, and 0.80 for "low", "medium", and "high" based on soil conditions. See Figure 4 for location of Sub-watersheds.**

Sub-Watershed (WS) Name	Soil Loss with low K value			Soil Loss with medium K value			Soil Loss with high K value		
	1"	2"	3"	1"	2"	3"	1"	2"	3"
	Mg	Mg	Mg	Mg	Mg	Mg	Mg	Mg	Mg
Ginger	185	739	1455	348	1389	2735	510	2038	4014
40 Acre	199	1055	2807	373	1983	5275	548	2910	7743
Upper North Trib - Wasabi	335	1868	4203	629	3511	7898	923	5153	11594
Upper North Trib - Brookbank	603	2941	6633	1133	5527	12465	1664	8113	18297
Middle North Trib	375	1956	4529	705	3677	8511	1035	5949	12493
Lower North Trib	196	837	1398	368	1573	2628	540	2309	3858
Lockett Ranches	367	2277	5793	689	4280	10887	1012	6283	15981
Paradise	197	1364	3596	370	2563	6759	544	3763	9921
Park Basins	192	1563	4272	361	2937	8028	530	4311	11784

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4.3 Sediment Transport and Retention

Empirical results from in-city sediment removal, as measured at the Cinder Hills Landfill, are provided
380 in Figure 9. The majority of sediment removed from the urban environment occurred after the first storms post-wildfire, during the July months. All in-city sediment removed is downstream of the modeling regimes and act as an end-point for the study system.
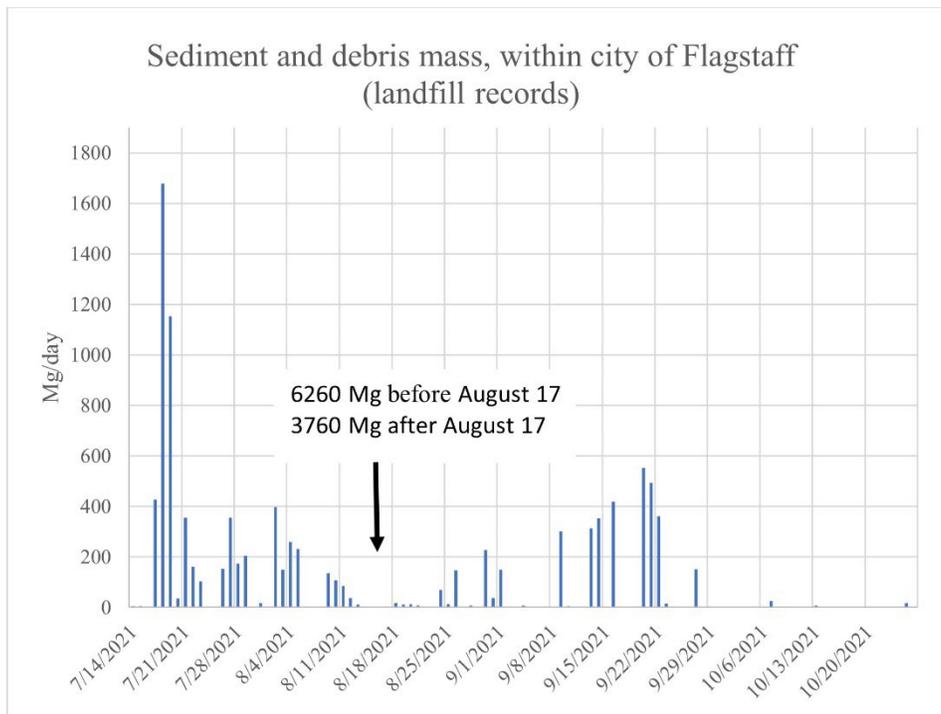
Figure 9. Sediment and debris removed from channels and streets. Flood events occurred on July 13, 14, 16, and August 17th. Flood flows were predicted at the upstream entry to the CoF as 20, 20, 28, and 44.7 m3/s respectively (Schenk et al. 2023).

The upstream FLOWSED/POWERSED sediment transport and on-forest retention modeling determined that five of the seven work area channel cross sections currently transport more sediment than is supplied to them, potentially leading to up gradient headcutting and continued erosion (highlighted in red in Table 3). These five proposed work area cross-sections transport 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.

Sediment transport modeling results (FLOWSED/POWERSED) indicate that design cross-sections retain an average of 70% of incoming sediment in proposed work areas than the degraded alluvial fans and channels in their current (fall 2021) condition (Table 3). 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 10a,b) however there were no flow events that over-topped the channel within the city to provide empirical comparisons. Observations of similarly designed sediment retention structures 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; Beers et al. 2023).

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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). The annual sediment transport rate to the city neighborhoods is outlined in yellow (4628 Mg/year).

Potential Work Area Name	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 Retention
-	(Mg/ year)	(Mg/ year)	(Mg/ year)	(Mg/year)	(Mg/year)	(Mg/year)	%
-	A	B	C	D	E	F	G
-	-	-	-	= A - B	= A - C	= E - D	= (1-C/A)*100
Ginger	377	324	54	54	324	270	78
40 Acre	992	1326	269	-335	722	1057	66
Upper North Tributary	532	3055	215	-2534	317	2840	54
Middle North Tributary	1128	1363	399	-235	728	963	59
Lower North Tributary	1290	2341	441	-1051	849	1901	60
Lockett Ranches	1814	1426	762	388	1052	664	53
Paradise	2028	4628	450	-2599	1579	4178	71

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A)   B)
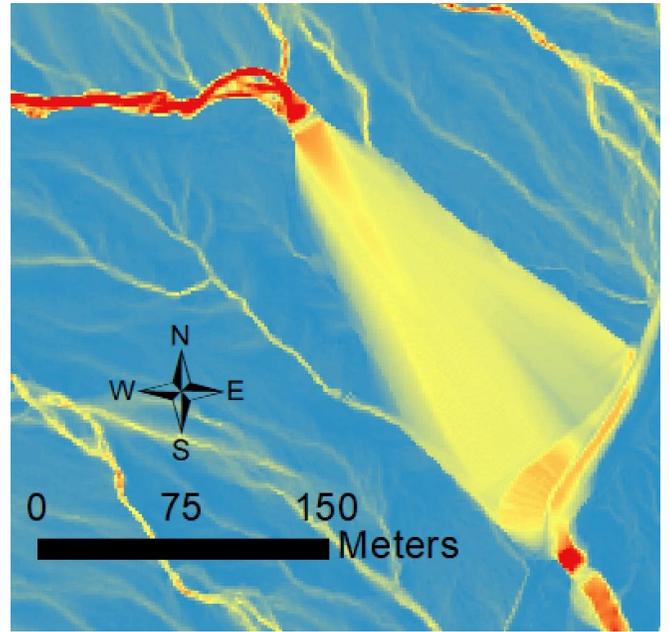
Figure 10 A) Ginger alluvial fan work site (35^0 15' 10", -111^0 38'0", looking upstream) during a July 2022 flow event, note the spread of flow and subsequent drop in water velocity allowing sediment aggradation. B) Ginger alluvial fan work site including predicted velocities during a 25 year annual exceedance probability rain event. The dark red areas are approximately 3 m/s, the blue areas denote no flow (0 m/s). The photograph in Figure 10a was taken at the southeast corner of the fan looking northwest (upstream).

The commonly used WEPP model demonstrated much lower sediment yields (3870 Mg/year) than the WARSSS model (4630 Mg/year) and empirical results (9900 Mg/year in 2021) for the Museum Fire burn scar and Spruce Wash watershed and slightly less than the event based MUSLE model (4860 Mg/year).

5. Discussion

The 2019 Museum Fire, and subsequent nearby 2022 Pipeline Fire, demonstrated that previous hydrologic forecasts for watershed disturbance in the northern Arizona region were largely correct. Two studies of local ponderosa pine (*Pinus ponderosa*) forests indicated that current conditions exhibited complacent watersheds, but that the threat of wildfire would enhance runoff by one to two orders of magnitude (Leao and Tecle, 2005; Quisenberry 2009), similar to observations in this burned watershed (Schenk et al. 2023; Sankey et al. 2024). Recent sediment risk predictions were also prescient, indicating orders of magnitude higher sediment transport post-disturbance (e.g. Neary et al. 2012; Natural Channel Design, 2012).

The four 2021 flooding events demonstrated a high sediment supply from the burn area with an observed rate of greater than 9,900 Mg into the neighborhoods from the four flood events alone. The WEPP and WARSSS models appear to underestimate sediment delivery by roughly 50% based on empirical observations of the above average monsoon season of 2021. A portion of the underestimation of both modeling regimes is the lack of ability to anticipate hillslope gully incision. The reasons for the relatively large contribution from hillslope gully and rill erosion 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
455   wildfires (Neary et al. 2012; Vanmaercke et al. 2021). 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 WARSSS and WEPP model
460   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). Other case studies have also shown that WEPP
underestimates post-wildfire erosion, as does MUSLE (e.g. Fernández and Vega, 2018; East et al. 2021),
there are still very few case studies of WARSSS for post-wildfire sediment modeling. The advantage of
465   WEPP, over WARSSS, is its ease of use, free availability, and rapid learning curve, allowing for rapid
spatial determination of high risk locations (Lew et al. 2022; East et al. 2024), however WEPPcloud
does not incorporate ground truthed data, as is evident when comparing spatial "hot spots" of sediment
yield in this case study. The WARSSS bank and hillslope predictions were informed by field
measurements that largely corresponded with qualitative observations of spatial sediment yield.

470   All three modeling domains, MUSLE, WEPP, and WARSSS showed drastic increases in channel and
hillslope sediment yields post-wildfire in this case study. Both WEPP and WARSSS predict slightly
more sediment yield from existing channels than from hillslope processes, however the hillslope gullying
and rill erosion is substantial. The similarity between model results, and less than an order of magnitude
comparison with empirical results, indicate that both WEPPcloud and WARSSS are useful for sediment
475   predictions. There has been some controversy about the use of "natural channel design" versus
"analytical channel design" for applied geomorphology projects (e.g. Lave 2009; Kasprak et al. 2016),
this case study suggests that both trains of thought have validity in the post-wildfire environment.
Continued updates to post-wildfire sediment modeling has been called for by disparate studies at a global
level (e.g. Lopes et al. 2021; Partington et al. 2022; Ebel et al. 2023) and the hope is this case study
480   provides support for future improvements in the post-wildfire sediment monitoring, modeling, and
applied mitigations arena.

For this case study, most high erosion areas are identified 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. Frequent debris flows, a separate sediment transport mechanism, also
485   complicates restoration in the headwater steep slopes (Porter et al. 2023; McGuire et al. 2023). 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 (Rosgen 2009). 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 (e.g. Hupp and
490   Simon 1991; Montgomery and Buffington 1993; Jumps et al. 2022). As such, there is a high potential
for substantial 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
495   of erosion, though that narrative is rapidly changing with more case studies and better landscape scale
surveying and monitoring (Neary et al. 2012; Rengers et al. 2016; McGuire et al. 2024). The poor
hillslope conditions are cause for concern if they do not begin to improve soon as high sediment loads
from hillslopes 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
500   hinder seed establishment further retarding recovery. The sediment transport models indicate a high
potential for successful reduction in sediment as flows cross restored alluvial fan areas, this was observed
in 2022 where observations at the nearby Pipeline Fire indicate a sediment retention greater than 70%
on the completed alluvial fan projects within some of the impacted watersheds (personal comms.
Lucinda Andreani, Coconino County Flood Control District Administrator). However, there were some
505   steep slope (>2%) alluvial fan work areas that performed poorly due to floods greater than the design
storm (Beers et al. 2023). 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.

The sediment mitigation structures, or "work areas", consist of an upstream, single thread "feeder" channel and a multithread anastomosing "fan" channel supported by lateral harden grade control (e.g. rock sills) before constricting back to a single thread channel to feed into the existing drainage downstream (see Beers et al. 2023 for more detail). Sediment output from the restored fans appears to be moderate over a long-term average (Beers et al. 2021). However, the relatively steep fans will produce higher shear stresses at high, infrequent flows. For example, peak discharges modeled for a 2" (5 cm) per hour precipitation event over the whole watershed (~ 37 CMS, 4% annual exceedance probability) produce enough shear stress on the Paradise fan to move 30 cm 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.

6. Conclusions

The need for accurate, and rapid, post-wildfire sediment yield and transport modeling is evident by the increased role of wildfires in the wildland-urban interface and subsequent flooding. This case study shows the utility of both WEPPcloud and WARSSS for predicting sediment transport to the city of Flagstaff, Arizona. The agreement between both models for sediment transport, and within an order of magnitude comparison to empirical observations from flood events in 2021, is encouraging. The difference between models was largely in the spatial pattern of sediment yield. Both models indicated a slightly higher contribution from channels than hillslopes but WARSSS, because it is partly empirically based, was better at identifying "hot spots" of both channel and hillslope sediment yield. Hillslope sediment yield nearly matched channels, indicating a high degree of hillslope gully and rill erosion, a process that needs further study. Continued advancements in post-wildfire sediment modeling will help inform managers and policy makers on sediment and flood mitigation strategies, planning, and design.

This study also introduced a post-wildfire sediment mitigation strategy through the restoration of alluvial fans. The fan "work areas" were identified using the POWERSED/FLOWSED sediment transport model, which was likewise informed by the sediment yield predictions of BANCs and ERMiT in the WARSSS model. Each restored fan work area included the removal of a single thread channel to a graded slope with lateral rock sills for grade control. These mitigations allow for the natural creation of an anastomosing channel that drops out sediment due to the change in shear stress and stream power. Initial sediment transport model results indicate a reduction in downstream sediment transport of 70%. Ongoing monitoring of these mitigation structures is occurring both in Spruce Wash as well as in adjacent burn scar areas in Coconino County, Arizona, initial results indicate success during small to moderate flow events.

Author contributions

Edward Schenk provided project administration, resources, visualization, data curation, funding acquisition, and writing. Alex Wood provided sediment investigation, formal analysis, writing, and data curation. Allen Haden provided methodology, project administration, funding acquisition, supervision, review, and resources. Gabriel Baca provided review and substantial editing, data curation, and formal analysis. Jake Fleishman provided data curation and formal analysis. Joe Loverich provided data curation and formal analysis including hydrology and FLO-2D modeling.

Competing Interests

The authors declare that they have no conflict of interest.

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