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Report No. UT-25.14

GEOSPATIAL TOOLKIT FOR RAPID ASSESSMENT OF POST-WILDFIRE SEDIMENTATION RISKS TO INFRASTRUCTURE

Prepared For:

Utah Department of Transportation
Research & Innovation Division

Final Report
April 2025

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ACKNOWLEDGMENTS

The authors acknowledge the Utah Department of Transportation (UDOT) for funding this research, and the following individuals on the Technical Advisory Committee for helping to guide the research:

- Jeff Erdman (UDOT)
- Sovann OK (UDOT)
- Rudy Alder (UDOT)
- Kaitlin Marousis (UDOT)
- Corey Unger (UDOT)
- Cody Alberts (UDOT)
- Brendan Waterman (USFS)
- Brett Roper (USFS)
- Dave Callery (USFS)
- Jamie Huff (UDPS)
- Kathy Holder (UDPS)

TECHNICAL REPORT ABSTRACT

1. Report No. UT-25.14	2. Government Accession No. N/A	3. Recipient's Catalog No. N/A
4. Title and Subtitle Geospatial Toolkit for Rapid Assessment of Post-Wildfire Sedimentation Risks to Infrastructure		5. Report Date April 2025 6. Performing Organization Code
7. Author(s) Scott R. David, Patrick Belmont, Brendan P. Murphy		8. Performing Organization Report No.
9. Performing Organization Name and Address Utah State University Department of Watershed Sciences 5210 Old Main Hill, NR 210 Logan, UT 84322		10. Work Unit No. 5H092 85H 11. Contract or Grant No. 23-8121
12. Sponsoring Agency Name and Address Utah Department of Transportation 4501 South 2700 West P.O. Box 148410 Salt Lake City, UT 84114-8410		13. Type of Report & Period Covered Final August 2022-May 2025 14. Sponsoring Agency Code PIC No. UT22.702

15. Supplementary Notes

Prepared in cooperation with the Utah Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration

16. Abstract

The UDOT Post-Wildfire Geohazard Assessment Toolkit is a GIS-based toolset designed to evaluate post-wildfire sediment hazards. The toolkit integrates precompiled geospatial datasets with user-supplied burn severity data to estimate debris flow probability, sediment production, and sediment delivery to river networks. The geospatial toolkit includes Direct Geohazard Impact Tools, which predicts debris flow triggering rainfall intensities and sediment volumes, and Downstream Impact Tools, which determine how much sediment is delivered to rivers from hillslope erosion and debris flows. The toolkit outputs spatially attributed datasets that integrated into 1-D watershed scale sediment transport models such as the Network Sediment Transporter (NST). To demonstrate its effectiveness, the toolkit was applied to five wildfire-impacted transportation corridors in Utah, identifying high-risk areas for sediment impacts. Results indicate that the toolkit provides a streamlined and scientifically robust method for assessing post-fire geohazards, supporting transportation agencies in emergency response planning and risk mitigation.

17. Key Words Post-Wildfire Geohazards, Infrastructure, Emergency Response, Sedimentation, Erosion, Sediment Routing, Debris-Flow		18. Distribution Statement Not restricted. Available through: UDOT Research Division 4501 South 2700 West P.O. Box 148410 Salt Lake City, UT 84114-8410 www.udot.utah.gov/go/research		23. Registrant's Seal N/A
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 77	22. Price N/A	

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UNIT CONVERSION FACTORS

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. (Adapted from FHWA report template, Revised March 2003)

LIST OF ACRONYMS

AOI	Area of Interest
BAER	Burned Area Emergency Response
BARC	Burned Area Reflectance Classification
DEM	Digital Elevation Model
dNBR	Differenced Normalized Burn Ratio
DOI	US Department of Interior
ERC	Energy Release Component
GUI	Graphical User Interface
MTBS	Monitoring Trends in Burn Severity
NST	Network Sediment Transporter
PRISM	Parameter-Elevation Regressions on Independent Slopes Model
RUSLE	Revised Universal Soil Loss Equation
SBS	Soil Burn Severity
SR	State Route
STATSGO	State Soil Geographic Database
TIGER	Topologically Integrated Geographic Encoding and Referencing
UDOT	Utah Department of Transportation

EXECUTIVE SUMMARY

Wildfires are increasing in frequency and severity across the western United States, posing significant risks to transportation infrastructure due to post-wildfire erosion and sedimentation hazards. Increased runoff from burned landscapes can trigger debris flows, accelerate hillslope erosion, and transport large volumes of sediment. These hazards threaten roads, bridges, and culverts, necessitating both rapid post-fire assessments and long-term proactive planning to mitigate risks. To address these challenges, the UDOT Post-Wildfire Geohazard Assessment Toolkit was developed as a GIS-based toolset to streamline the evaluation of post-fire sediment hazards and their impacts on transportation infrastructure.

This report focuses on the application of the toolkit for emergency response assessments, enabling transportation planners to rapidly evaluate post-fire geohazards following a wildfire event. The toolkit integrates state-of-the-art geospatial analysis techniques to estimate debris flow probability, sediment production, and sediment delivery to river networks. It consists of two primary components:

- Direct Geohazard Impacts Toolkit, which assesses post-fire debris flow hazards along transportation corridors, predicting debris flow triggering rainfall intensities and estimating eroded sediment volumes.
- Downstream Impacts Tools, which estimate the volume of post-fire sediment delivered to river networks from both debris flow and hillslope erosion processes. These tools attribute sediment delivery data to shapefiles, allowing for integration with external sediment transport models (e.g., NST) to assess downstream impacts on infrastructure such as bridges and culverts.

The toolkit leverages a combination of precompiled geospatial datasets and user-supplied burn severity data to automate the assessment process. Key inputs include topography, precipitation intensity, annual precipitation, land cover, soil properties, and burn severity data. The workflow is designed to be intuitive for ArcGIS users, allowing for rapid extraction of relevant datasets and automated computation of post-fire sediment hazards.

To demonstrate the toolkit's capabilities, we applied it to five case study sites across Utah, each impacted by a recent wildfire:

- SR 143 (Brian Head Fire, near Parowan, UT)
- US 89/6 (Pole Creek Fire, near Spanish Fork, UT)
- SR 40 (Dollar Ridge Fire, near Duchesne, UT)
- US 6 (Bear Fire, near Helper, UT)
- SR 196 (Big Springs Fire, near Tooele, UT)

Results from these simulations highlight the effectiveness of the toolkit in identifying high-risk locations where sediment deposition could impact transportation infrastructure.

The UDOT Post-Wildfire Geohazard Assessment Toolkit provides a scientifically robust and user-friendly framework for assessing post-fire sedimentation hazards. By equipping transportation agencies with actionable data, the toolkit supports informed decision-making, enabling more effective risk mitigation strategies and resource allocation.

1.0 INTRODUCTION

1.1 Problem Statement

Wildfires are a natural component of their western U.S. landscapes, but their frequency and severity have increased dramatically over the past 40 years (Murphy et al., 2018). The increased intensity and spatial extent of wildfires is driven by a combination of climate change (Abatzoglou & Williams, 2016), and fire suppression policies that have allowed fuel loads to accumulate (Murphy et al., 2018). Post-wildfire landscapes exhibit profoundly altered hydrology, often leading to increased runoff and erosion following rainfall events (McGuire et al., 2024). These effects increase post-fire landscape erosion, and the heightened sediment loads can impact infrastructure after the fire is extinguished.

Post-fire sedimentation poses a significant risk to transportation infrastructure, as roadways, culverts, and bridges may experience blockage, scour, or structural failure. In Utah, multiple high-cost post-fire sedimentation events have occurred in recent years, such as damage to Highway 143 in Parowan Canyon (2017) and US 89 near Birdseye, Utah (2019) due to post-fire flooding and sedimentation. More recently, post-wildfire erosion in Crandall Canyon resulted in increased sediment loads being delivered to Price Canyon, near Helper Utah. The increased sediment loads caused significant damage to a culvert costing ~3.5 million dollars in repairs. Hence, being able to predict the locations of these impacts prior to the occurrence is an important step towards being able to plan conservation, mitigation, and post-fire landscape rehabilitation efforts to reduce impacts to transportation corridors.

To date, several existing models provide post-wildfire hazard assessments, but they have notable limitations. The USGS Hazards Model (Gartner et al., 2014; King, 2024; Staley et al., 2017), is widely used for debris flow probability and volume predictions. However, this model requires advanced Python scripting knowledge, assumes uniform rainfall intensities across watersheds, and does not estimate sediment delivery to river networks. Additionally, the USGS Hazards Model only delineates sub-catchments from rivers making it difficult to infer potential direct hazards to transportation infrastructure. The WEPP-PEP (Water Erosion Prediction Project - Post-Fire Erosion Prediction) model offers an online interface but lacks debris flow analysis, operates as a black-box tool with limited user customization, and is not easily integrated into broader modeling workflows.

To address these limitations, we developed the UDOT Post-Wildfire Geohazard Assessment Toolkit, which allows for a rapid, GIS-based assessment of post-fire erosion and sedimentation hazards. This toolkit supports both emergency response efforts immediately after wildfires and long-term planning for wildfire-prone regions. While this report focuses on the emergency response application, a separate UDOT report (UT-25.13) will describe its use in proactive risk planning. Lastly, we demonstrate the applicability of the toolkit at five test locations where fire has occurred.

1.2 Objectives

The primary objective of this study is to develop a GIS-based post-wildfire hazard assessment toolkit that:

1. Creates easy to use landscape scale delineations and characterization that directly incorporates transportation infrastructure.
2. Provides a structured yet flexible workflow for evaluating sediment delivery from post-fire debris flows and hillslope erosion.
3. Integrates with network-scale sediment transport models, such as the Network Sediment Transporter (NST), for predicting sediment movement through river networks.
4. Allows users with limited programming experience to conduct post-fire geohazard assessments through an intuitive ArcGIS-based Graphical User Interface (GUI).
5. Support both emergency response applications (e.g., post-fire hazard assessment) and proactive planning (e.g., pre-fire geohazards assessments; see UDOT report UT-25.13).

A secondary objective of this report is to demonstrate the application of the toolkit for five emergency response applications in Utah, identified with assistance from our Technical Advisory Committee:

1. State Route 143 (Brian Head Fire, near Parowan, UT)
2. U.S. Route 89/6 (Pole Creek Fire, near Spanish Fork, UT)
3. State Route 40 (Dollar Ridge Fire, near Duchesne, UT)
4. U.S. Route 6 (Bear Fire, near Helper, UT)
5. State Route 196 (Big Springs Fire, near Tooele, UT)

1.3 Scope

This research develops a geospatial modeling framework that allows users to estimate sedimentation hazards at the watershed scale incorporating debris flow and hillslope erosion processes.

The geospatial toolkit consists of two primary assessments:

1. Direct Post-Fire Geohazard Assessment – Evaluates debris flow hazards along transportation corridors by estimating debris flow probability, and eroded sediment volumes upslope of transportation corridors. This assessment follows USGS methodologies (Staley et al., 2017; Gartner et al., 2014) but improves upon them by allowing for custom rainfall inputs and transportation-focused evaluations.

2. Downstream Post-Fire Geohazard Assessment – Computes sediment volumes mobilized by both debris flows and hillslope erosion, then determines how much of this sediment is delivered to the river network. The outputs are built to easily incorporate into 1-D network scale sediment transport models allowing users to simulate sediment delivery to downstream infrastructure (e.g., bridges and culverts).

The toolkit relies on multiple geospatial datasets, including digital elevation models (DEMs), land cover data, soil properties, burn severity maps, and rainfall intensity estimates. The toolkits presented here allow for transportation planners and emergency response teams to quickly assess post-fire sedimentation hazards.

2.0 Geospatial Model Description

2.1 Overview

The UDOT Post-Wildfire Geohazard Assessment Toolkit is a set of Python-based scripts built on the ESRI ArcGIS platform, developed using ArcGIS Pro 3.4. The toolkit requires a basic ArcGIS Pro license, along with Spatial Analyst and 3D Analyst extensions. It provides users with an intuitive ArcGIS toolbox GUI, enabling tools to be executed individually or in sequence. Additionally, the underlying Python code can be accessed and executed within ArcGIS or externally using a Python Integrated Development Environment (IDE) such as Spyder or PyCharm.

The geospatial tools were designed to support both emergency response (post-wildfire) and proactive planning (pre-fire sediment hazard assessment). This report focuses on the toolkit's emergency response applications, demonstrating its role in rapid post-fire geohazard assessment. A separate UDOT report (UT-25.13) addresses the toolkit's application in proactive planning for post-wildfire sediment hazards in transportation corridors.

The following sections detail the toolkit's components described in terms of functionality, required inputs, and generated outputs:

- Preprocessing tools for preparing geospatial inputs (Section 2.2).
- Post-Fire Direct Geohazard Assessment tools, which analyze debris flow hazards along transportation networks (Section 2.3).
- Post-Fire Downstream Geohazard Assessment tools, which model post-fire sediment erosion and delivery to river networks (Section 2.4). The outputs from this section are formatted to be directly used in network-scale sediment transport models.

2.2 Preprocessing Tools

The preprocessing tools included in the UDOT Post-Wildfire Geohazard Assessment Toolkit ensure that input datasets are properly formatted, classified, and spatially aligned before being used in geohazard assessments. These tools allow users to extract, classify, and standardize geospatial datasets, ensuring compatibility with subsequent analysis workflows. The preprocessing tools include Batch Extract Inputs, Create Burn Severity (BARC 4) Map, and Clean Burn Severity Data.

2.2.1 Batch Extract Inputs

The Batch Extract Inputs tool processes geospatial data by clipping, resampling, and snapping input datasets to a specified area of interest (AOI). This ensures that all input data layers, including raster and vector datasets, are spatially consistent for analyses. The tool is designed to streamline preprocessing by standardizing datasets before further geohazard modeling. Specifically, all raster datasets are resampled to match the cell resolution of the digital elevation model (DEM), and all outputs are clipped to the AOI boundary with a uniform spatial projection. Additionally, the tool maintains the same subdirectory structure as in the Input Data Directory, ensuring organizational consistency for users.

A pre-configured Input Data Directory is available, containing all required statewide files for running simulations across Utah, except for valley bottom data and fire data, which must be provided separately by the user.

Users must provide three inputs:

- Input Area of Interest – A polygon shapefile defining the study area.
- Input Data Directory – A folder containing statewide raster and vector datasets. This directory must include a DEM subfolder that stores the digital elevation model.
- Output Data Directory – The location where clipped and resampled datasets will be stored.

The tool generates a set of clipped and standardized datasets that match the AOI's extent and coordinate system. All raster datasets are resampled and snapped to the DEM's resolution, ensuring spatial consistency. Vector datasets are clipped to the AOI boundary, and all outputs are saved in the designated Output Data Directory, preserving the original folder hierarchy. These standardized datasets serve as the foundation for subsequent geospatial analyses within the UDOT Post-Wildfire Geohazard Assessment Toolkit.

2.2.2 Create Burn Severity (BARC 4) Map

The Create Burn Severity (BARC 4) Map tool classifies differenced Normalized Burn Ratio (dNBR) raster data into a standardized four-class Burned Area Reflectance Classification (BARC 4) raster. The tool applies user-defined or default threshold values to bin continuous dNBR values into four classes representing burn severity levels: 1 – Unburned, 2 – Low Severity, 3 – Moderate Severity, and 4 – High Severity. By default, the tool uses Utah-specific thresholds based on Klimas et al. (2025), but users may adjust these thresholds as needed; the in-tool help dialogue also provides alternative thresholds commonly used by the USGS. While the resulting BARC 4 raster provides a useful approximation of burn severity, it is not a true Soil Burn Severity (SBS) product. If a field-validated SBS raster is available from a Burned Area Emergency Response (BAER) team, it should be used in place of the BARC 4 map. BARC classifications are frequently modified during BAER field assessments to better reflect observed soil burn conditions (e.g., Clark, 2013; Wilson & Prentice, 2024).

2.2.3 Clean Burn Severity Data

The Clean Burn Severity Data tool refines burn severity rasters, such as those derived from Burned Area Reflectance Classification (BARC) maps or field-validated Soil Burn Severity (SBS) datasets, by removing invalid or no data values that may be present in these products. Burn severity rasters often contain values outside the standard 1–4 classification, where certain values may represent missing data, unburned areas, or increased post-fire greenness rather than burn severity. This tool reclassifies all values outside the range of 1–4 as NoData, ensuring that the resulting raster retains only valid burn severity classes. The NoData designation is recognized by GIS software such as Esri products, making the output raster ready for further analysis or visualization.

2.3 Direct Impacts

The Direct Post-Fire Geohazard Impacts tools are designed to evaluate how debris flows impact transportation corridors following a wildfire. This toolset allows users to delineate sub-catchments draining directly to transportation corridors, estimate the rainfall intensity required to generate a particular probability or likelihood of a debris flow occurring, and calculate debris flow eroded sediment volumes.

This section contains:

- Direct Impacts Wrapper – A tool that runs the following three sub-tools in sequence, creating a more streamlined experience.
- Delineate Sub-catchments from Roads – A modified sub-catchment delineation tool that defines drainage areas based on roads rather than rivers.
- Debris Flow Rainfall Intensity – Calculates the 15-minute rainfall intensity (Staley et al., 2017) required to trigger debris flows based on a user-defined probability of debris flow occurrence.
- Debris Flow Volume– Estimates the volume of sediment eroded by debris flows for the calculated 15-minute rainfall intensity threshold (Gartner et al., 2014).

The tools can be run individually or together using the wrapper tool, depending on user needs.

2.3.1 Direct Impacts Wrapper Tool

The Direct Impacts Tool automates the execution of all three direct impact tools in a single workflow. Instead of running the Delineate Sub-catchments, Debris Flow Rainfall Intensity, and Debris Flow Volume tools separately, this wrapper ensures that they are processed sequentially with consistent inputs and outputs creating a streamlined, easy-to-use approach that allows for rapid assessment of direct post-fire geohazards impacts to transportation corridors.

The tool requires users to input a DEM, a delineated infrastructure corridor as a polyline or polygon, a Soil Burn Severity and dNBR raster, a shapefile delineating the burn perimeter of the wildfire, and a STATSGO soil dataset attributed with soil erodibility data (kffact) and soil thickness (in cm). Additionally, users set a threshold value for a minimum value for sub-catchment area threshold (in km^2) to set the minimum drainage area to be considered a sub-catchment. The maximum drainage area to be considered a sub-catchment is 10 km^2, as that is the upper limit of catchment areas used to generate the debris flow probability model (Staley et al., 2017). Users can specify a buffer radius around the input transportation corridor to automatically adjust the width of the corridor. Finally, the user needs to specify a debris flow probability value that will be used to compute the rainfall intensity that needs to occur in each sub-catchment to achieve that probability of a debris flow occurring.

The primary output from this tool is a sub-catchment shapefile, attributed with the 15-minute rainfall intensity required to achieve the user-defined debris flow probability and the resulting debris flow volume (Table 1), however the attribute table also contains all required parameters used to execute the calculations.

Table 1. List of attributes and descriptions generated by the Direct Impacts Tools workflow.

Field Name	Description	Units	Generated By
area	Sub-catchment area	km^2	Delineate Sub-Catchments from Roads
trib	Binary indicator if sub-catchment drains to a tributary (0 = No, 1 = Yes)	None	Delineate Sub-Catchments from Roads
sub_ID	Unique sub-catchment identifier	None	Delineate Sub-Catchments from Roads
Burned	Binary indicator if sub-catchment burned (0 = No, 1 = Yes)	None	Debris Flow Rainfall Intensity
k_factor	Soil erodibility factor	None	Debris Flow Rainfall Intensity
area_MH_23	Percent area burned at moderate to high severity	km^2	Debris Flow Rainfall Intensity
avgdNBR	Average differenced Normalized Burn Ratio	None	Debris Flow Rainfall Intensity

df_prob	User-defined debris flow probability	None	Debris Flow Rainfall Intensity
i15	15-minute rainfall intensity	mm/hr	Debris Flow Rainfall Intensity
mh_ln_area	Natural log of moderate-to-high severity burn area	ln(km²)	Debris Flow Volume
relief	Basin relief	m	Debris Flow Volume
soilvol_m3	Volume of soil available for erosion	m³	Debris Flow Volume
GVol	Predicted debris flow volume from Gartner model	m³	Debris Flow Volume
Gsupp_lim	Binary indicator if debris flow is supply-limited (0 = No, 1 = Yes)	None	Debris Flow Volume
Gsl_vol	Sediment volume supplied under supply-limited conditions	m³	Debris Flow Volume
GFrSoilLos	Fraction of available soil lost due to debris flow	None	Debris Flow Volume

2.3.2 Delineate Sub-Catchments from Roads

The Delineate Sub-Catchments from Roads tool modifies traditional sub-catchment delineation (David et al., 2023) by automatically identifying pour points based on transportation corridors rather than rivers. The tool then delineates all sub-catchments draining to the identified pour points, provided their drainage areas exceed a user-defined threshold (km²). If a delineated sub-catchment exceeds 10 km², the tool subdivides it by identifying all points draining to cells with a flow accumulation of 10 km² or greater and delineating sub-catchments draining to each of those points. This upper threshold ensures that the resulting sub-catchments remain within the spatial domain required to run post-wildfire debris flow hazard models (Staley et al., 2017).

To use this tool, users must provide a Digital Elevation Model (DEM), an infrastructure corridor dataset representing the road network (polyline or polygon), and a buffer radius to define the area of influence around roadways. Additionally, users set a minimum sub-catchment area threshold, ensuring that only drainage areas exceeding this threshold are included in the analysis. The tool outputs a sub-catchment polygon shapefile, where each unit represents a unique drainage area that flows toward a transportation corridor.

2.3.3 Debris Flow Triggering Rainfall Intensity

The Debris Flow Rainfall Intensity tool estimates the rainfall intensity required to produce a user-defined probability of debris flow occurrence following a wildfire. Based on the probabilistic model (eqn. 1) developed by Staley et al. (2017), this tool calculates the 15-minute rainfall intensity necessary to trigger debris flows in burned areas, incorporating site-specific burn severity and soil conditions.

$$R_{i15} = \frac{\ln\left(\frac{P}{1-P}\right)+3.63}{(0.41 \cdot A_{\mathrm{mh23}})+(0.67 \cdot \overline{\mathrm{dNBR}})+(0.7 \cdot \overline{K_f})} \cdot 4 \qquad \textit{eqn .1}$$

Where, R_{i15} is the15-minute rainfall intensity threshold (mm/hr), P is the user-defined debris flow probability threshold, A_{mh23} is the proportion of the basin area that burned at moderate to high severity on slopes ≥ to 23 degrees, $\overline{dNBR}$ is the mean dNBR for a sub-catchment, and $\overline{K_f}$ is the mean soil erodibility factor (K-factor) for a sub-catchment.

Users must provide Soil Burn Severity and dNBR rasters, STATSGO soil data shapefile attributed with a soil erodibility factor, a burn perimeter shapefile, and a user-defined debris flow probability threshold. The tool can either update the attribute fields of the input sub-catchments or create a new copy of the input sub-catchments shapefile attributed with the computed triggering 15-min rainfall intensities and the values used for computation (Table 1):

2.3.4 Debris Flow Volume

The Debris Flow Volume tool estimates the volume of sediment eroded by debris flows based on the calculated 15-minute rainfall intensity. Utilizing the empirical model developed by Gartner et al. (2014), this tool predicts debris flow volume by incorporating burn severity, soil properties, and watershed characteristics.

$$V = e^{\left(4.22+\left(0.39 \cdot \sqrt{i_{15}}\right)+\left(0.36 \cdot \mathbf{ln}(MH_{\boldsymbol{km}})\right)+\left(0.13 \cdot \sqrt{R}\right)\right)} \qquad \text{eqn. 2}$$

Where, V is the estimated debris flow volume (m^3), $i15$ is the 15-minute rainfall intensity (mm/hr), MH_{km} is the upstream burned area at moderate to high severity (km^2), and R is the sub-catchment relief (m).

The tool requires the user to input a Soil Burn Severity raster, STATSGO shapefile attributed with soil thickness, a burn perimeter shapefile, and a sub-catchment shapefile attributed with the 15-minute rainfall intensity required to achieve the user defined debris flow probability from section 2.3.3. The tool can either update the input sub-catchment file or generate a new shapefile attributed with required metrics for computing debris flow volumes and the resulting volume estimates (Table 1). Additionally, the tool performs a check to ensure the debris flow is not eroding more soil than is available in the catchment.

2.4 Downstream Impacts

While direct post-fire geohazards pose immediate risks to transportation infrastructure, sediment mobilized by debris flow and hillslope erosion can create long-term downstream impacts, particularly at locations where transportation corridors intersect rivers (e.g., culverts, bridges). The Downstream Impacts tools estimate how post-wildfire sediment is delivered to river systems, providing essential inputs for initializing 1-D network-scale sediment routing models to assess downstream risks to transportation infrastructure. This analysis consists of two primary toolsets:

1. Infra-USUAL Watershed Tools – Performs landscape-scale delineations, characterization, and attribution to prepare river networks for sediment transport modeling. This toolkit builds on David et al. (2023) but includes new functionality, such as:

    - The Utah StreamStats tool, which runs USGS stream statistics calculations to derive bankfull width & depth (Bieger et al., 2015) and peak-flow statistics (Kenney et al., 2007).

    - User-defined breakpoints for river discretization, allowing users to specify infrastructure-based split locations rather than relying solely on a set distance.

2. Infra-WEST – Computes post-fire erosion from multiple processes and sediment delivery to river networks by integrating a suite of individual models.

    - Debris flow probability (Staley et al., 2017), erosion (Gartner et al., 2014) and runout (Murphy et al., 2019) models estimate debris flow initiation, volume, and delivery to streams.

    - Hillslope erosion and delivery models (RUSLE) estimates sediment input to river networks from hillslope processes (Gannon et al., 2019).

    - Output post-processing tools to prepare data for 1-D network scale sediment transport models.

The following sections describe each toolset and their individual tools in detail, outlining their purpose, required inputs, and generated outputs.

2.4.1 Infra-USUAL: Landscape Characterization

The Infra-USUAL Watershed Tools is a modified version of the USUAL Watershed Tools (David et al., 2023), designed to delineate landscapes, classify process domains, and attribute river networks for landscape-scale network modeling. These tools perform watershed delineation, sub-catchment and interfluve delineation, and river network attribution. This toolkit follows the same core methodology as David et al. (2023) but introduces two key modifications to streamline post-wildfire sediment assessments for transportation infrastructure in Utah:

- Utah StreamStats Integration – Computes bankfull width and depth using regional hydraulic geometry regression equations (Bieger et al., 2015), following the same workflow as the USGS StreamStats tool.

- User-Defined Breakpoints for River Discretization – Instead of relying solely on fixed distances, users can now specify infrastructure-based split locations, allowing for custom river discretization at key locations such as culverts, bridges, and road crossings.

By incorporating these modifications, Infra-USUAL enables users to generate a river network specifically structured for assessing post-wildfire sediment hazards at transportation infrastructure locations. The following subsections introduce a wrapper script that runs this full workflow as a single tool and describe new and modified tools beyond those in the USUAL Watershed Tools workflow. For details on the core methodology and underlying tools see David et al. (2023).

2.4.1.1 Infra-USUAL Wrapper

The Infra-USUAL Wrapper automates the workflow for delineating watersheds, sub-catchments, interfluves, and discretized river networks, ensuring they are fully attributed for sediment transport modeling. By integrating multiple processing steps into a single tool, it streamlines the user experience, making it quick and efficient to generate hydro-geomorphic delineations. The tool supports both single-site and nested basin analyses. A nested basin analysis is particularly useful in watersheds with local sediment sinks (e.g., reservoirs), allowing users to generate a series of nested watersheds, each with its own output subdirectory for organized data management.

To run the Infra-USUAL Wrapper, users must provide a DEM and define input pour points that serve as watershed outlets. Pour points are supplied as a point shapefile, with unique identifiers selected from a specified field, enabling multi-site processing (e.g., nested basin analysis). Users can also input infrastructure point locations (e.g., bridges, culverts) to discretize the river network at key locations, ensuring finer spatial resolution where needed. If infrastructure points do not align with the river network, the tool automatically snaps them to the delineated stream network. Additional inputs include a hydro-physiographic region dataset, which is required for hydraulic geometry regressions, and an optional AOI shapefile to constrain the analysis and reduce computational costs. Users must also specify threshold values for river network extraction, sub-catchment delineation, and minimum river slopes to tailor the analysis to the study area.

The tool generates multiple output datasets (Table 2), including a filled DEM, watershed, sub-catchment, and interfluve shapefiles, and a fully attributed river network. The river network is segmented based on user-defined breakpoints and a fixed discretization length and is attributed (Table 3) with bankfull width and depth estimates (Bieger et al., 2015) derived from the USGS StreamStats regression equations. Additional attributes include valley bottom width, river slope, and discharge estimates for multiple recurrence intervals (Kenney et al., 2007). When running a nested basin analysis, the tool organizes outputs into subdirectories for each processed basin.

Table 2. Key outputs from the Infra-USUAL Watershed Tools

Output	Description	Format	File Name Format
Watershed Extent	Boundary of the analyzed watershed.	Shapefile	basename_watershed.shp
River Network	Attributed polyline representing the river system with hydraulic geometry, flow metrics, and infrastructure-based segmentation.	Shapefile	basename_network.shp
Sub-Catchments	Polygon units representing the drainage areas for sediment delivery calculations.	Shapefile	basename_subcatchments.shp
Interfluves	Polygon units separating hillslope and channel domains for erosion modeling.	Shapefile	basename_interfluves.shp
Valley Bottom Transects	Cross-sectional profiles used to estimate valley bottom width.	Shapefile	basename_trans.shp
Flow Direction Raster	Derived flow directions from the filled DEM.	Raster	basename_fdr.tif
Flow Accumulation Raster	Raster indicating accumulated flow at each cell.	Raster	basename_fac.tif

Filled DEM	Hydrologically corrected DEM ensuring continuous flow paths.	Raster	basename_demf.tif
Infrastructure-Snapped Points	Road/bridge locations snapped to the river network.	Shapefile	basename_infrastructure_snapped.shp
Network Nodes	Point dataset identifying breaks between river network segments	Shapefile	basename_nodes_network.shp

Table 3: River Network Attributes

Field Name	**Description**	**Units**
FID	Feature ID	None
Shape	Geometry type	None
Id	Unique segment identifier	None
ORIG_FID	Original feature ID	None
ORIG_SEQ	Original sequence number	None
GridID	Unique river network segment identifier	None
Length_m	Segment length	m
ToLink	Downstream connectivity (ID of the next downstream segment)	None
usarea_km2	Upstream contributing area	km^2
uselev_m	Elevation at the upstream end of the segment	m
dselev_m	Elevation at the downstream end of the segment	m
Slope	Channel slope	None
VB_Width	Valley bottom width	m

Qcms2yr	Estimated 2-year recurrence interval flow	cms
Qcms5yr	Estimated 5-year recurrence interval flow	cms
Qcms10yr	Estimated 10-year recurrence interval flow	cms
Qcms25yr	Estimated 25-year recurrence interval flow	cms
Qcms50yr	Estimated 50-year recurrence interval flow	cms
Qcms100yr	Estimated 100-year recurrence interval flow	cms
Qcms200yr	Estimated 200-year recurrence interval flow	cms
Qcms500yr	Estimated 500-year recurrence interval flow	cms
RMS_BFw_m	RMS bankfull width estimate	m
RMS_BFd_m	RMS bankfull depth estimate	m
IMP_BFw_m	Improved bankfull width estimate	m
IMP_BFd_m	Improved bankfull depth estimate	m
Lev_Width	Estimated levee/floodplain exchange width	m
in_RES	Binary indicator if the segment is within a reservoir (0/1)	None

2.4.1.2 Discretize and Attribute River Network

The Discretize and Attribute River Network tool discretizes and attributes river networks at a user defined maximum length and locations where transportation corridors cross rivers (e.g., bridges or culverts.) In David et al. (2023), river networks were discretized solely using fixed-distance segmentation. This updated version refines the discretization process by allowing users to define infrastructure-based breakpoints, ensuring that culverts, bridges, and other critical transportation crossings are explicitly represented allowing users to assess sediment fluxes between river links at exact locations.

To run this tool, users must provide a delineated river network shapefile and a set of user-defined breakpoints as a point shapefile. These breakpoints represent locations where transportation corridors intersect the river network, ensuring that culverts, bridges, and other infrastructure are explicitly incorporated into the discretization process. The tool segments the river network at these locations while also applying a fixed-distance discretization method, which is required for consistency in downstream modeling. Additional inputs include a flow accumulation raster and a filled DEM, which are necessary for computing segment attributes such as contributing drainage area and slope. Users must also specify a minimum river slope threshold, below which slope calculations are not performed. This threshold is important for ensuring numerical stability in 1-D network sediment transport models, where very low slopes can lead to instabilities. Finally, users define an output directory and output basename, which determines where and the output name the processed river network and associated attributes are stored.

The tool outputs an updated river network shapefile (Table 3), where segments are split at user-defined locations and attributed with a unique identifier, drainage area, upstream and downstream elevation, slope, and downstream connectivity.

2.4.1.3 Utah-StreamStats

The Utah StreamStats tool applies USGS StreamStats regional regression equations to estimate peak streamflows (Kenney et al., 2007) and hydraulic geometry attributes (Bieger et al., 2015) for river networks. The tool differentiates between the Rocky Mountain West and Intermountain Plateau physiographic regions to ensure regionally appropriate estimates.

To run this tool, users must provide a river network shapefile attributed with a drainage area field, a watershed extent shapefile to constrain the analysis, a DEM, and a geohydrologic regions (Kenney et al., 2007) shapefile to determine the appropriate regression equations. Additional inputs include an annual precipitation raster and a land cover raster. Users must also specify an output basename, which determines the naming convention for results, and a temporary folder for storing intermediate files.

The tool outputs an updated river network shapefile (Table 3) attributed with discharge estimates for multiple recurrence intervals (2-, 5-, 10-, 25-, 50-, 100-, 200-, and 500-year events) as well as bankfull width and depth estimates.

2.4.2 Infra-WEST

The Infra-WEST toolkit is designed to estimate sediment generation from post-fire debris flows and hillslope erosion and determine how much of this sediment is delivered to river networks. Infra-WEST provides a streamlined approach for evaluating post-fire sediment hazards and their potential impacts on fluvial networks.

The Infra-WEST Wrapper automates this multi-step workflow outlined below, ensuring seamless data integration across its component models. The toolkit consists of six primary tools:

- Debris Flow Probability– Computes the probability of post-fire debris flow (Staley et al., 2017).
- Debris Flow Volume – Estimates the volume of sediment eroded by post-fire debris flows (Gartner et al., 2014).
- Debris Flow Delivery – Predicts the proportion of debris flow sediment that reaches the river network based on eroded volumes and valley bottom geometry (Murphy et al., 2019).
- Post-Fire Hillslope Erosion– Computes sediment yield from hillslope processes using a post-fire modified version of the Revised Universal Soil Loss Equation (RUSLE) (Gannon et al., 2019).
- Upstream Burn Area Calculator – Determines the fraction of moderate-to-high severity burned area upstream of each river segment, which is useful for post-fire flow scaling.
- Prepare NST Data – Prepares the sediment generation outputs from Infra-WEST for integration into the Network Sediment Transporter (NST) model by structuring sediment delivery inputs and incorporating river-floodplain exchange processes.

The following sections describe each tool in detail, outlining their purpose, required inputs, and generated outputs.

2.4.2.1 Run Downstream Infra-WEST Wrapper

The Infra-WEST Wrapper automates the execution of all Infra-WEST tools, ensuring seamless data integration across the workflow. This script processes terrain, burn severity, soil, land cover, and hydrologic datasets to compute post-wildfire sediment hazards and their potential impacts on river networks.

To run the Infra-WEST Wrapper, users must provide a DEM, flow accumulation and direction rasters, watershed extent, a river channel mask raster, and a fire perimeter shapefile. Additionally, the wrapper requires sub-catchments and interfluves shapefiles (with corresponding pour points), a river network shapefile, and a STATSGO soil shapefile attributed with soil erodibility (K-factor), soil thickness, bulk density, and percent sand. Other required inputs include a land cover raster, annual precipitation raster, SBS raster, and dNBR raster. Users must also specify a 15-minute precipitation intensity as either a constant value or a raster. Lastly, the script requires a levee width field, which is generated by the infra-USUAL wrapper or can be generated using the ArcGIS Calculate Field Function, and an output base name, which standardizes the filenames of generated datasets.

The Infra-WEST Wrapper outputs new copies of the input river network, sub-catchments and interfluves attributed post-fire sediment data. This includes predictions of debris flow probability, erosion and delivery, hillslope erosion and delivery, riverbed aggradation, and floodplain deposition. The script also determines whether sediment overfills the valley bottom and routes excess sediment downstream accordingly. The final output provides an NST-ready river network shapefile, ensuring compatibility with post-processing sediment transport simulations. Key output attributes generated by the Infra-WEST Wrapper are summarized in Table 4.

Table 4: Attributes Generated by Infra-WEST

Attribute Name	Description	Shapefile
df_prob	Probability of debris flow initiation, based on Staley et al. (2017)	Sub-Catchments
avg_i15	Average 15-minute rainfall intensity (mm) used in debris flow probability calculations	Sub-Catchments
G14Vol	Estimated debris flow volume (m³) from Gartner et al. (2014)	Sub-Catchments

G14sl_vol	Supply-limited debris flow sediment volume (m^3)	Sub-Catchments
VolDelTot	Total debris flow sediment volume (m^3) delivered to the river network	Sub-Catchments
VolDelLoc	Local debris flow sediment volume deposited at the sub-catchment outlet	Sub-Catchments
VolDelDstr	Volume of sediment routed downstream due to valley bottom sediment storage capacity being exceeded	Sub-Catchments
Scenario	Numerical identifier of the debris flow delivery scenario based on Murphy et al. (2019)	Sub-Catchments
RunoutLen	Estimated debris flow runout length (m)	Sub-Catchments
DstDwnstrm	Distance debris flow sediment was further downstream (m)	Sub-Catchments
Rmaxthic	Maximum estimated sediment deposition thickness in downriver sediment wedge (m)	Sub-Catchments
dbfDelDstr	Volume (m^3) of debris flow sediment routed downstream	River Network
SCidDdstr	Sub-catchment IDs contributing sediment to a river reach	River Network
PercVol	Percentage of the total sediment volume in a river reach from each contributing sub-catchment	River Network
USMH	Fraction of upstream drainage area burned at moderate-to-high severity	River Network
iDBFVol	Estimated debris flow sediment volume deposited in the river reach	River Network
aDBFVol	Adjusted debris flow sediment volume deposited after river-floodplain exchange	River Network
ChanFrac	Fraction of sediment retained within the river channel	River Network
LeveeFrac	Fraction of sediment deposited in the floodplain/levee areas	River Network

LeveeH	Height of the levee generated from river-floodplain exchange	River Network
newBfDepth	Updated bankfull depth after sediment deposition	River Network
RFVol	Volume of fine-grained RUSLE sediment input to the network in year 1	
RCVol	Volume of coarse grained (sand) RUSLE sediment input to the network in year 1	River Network
TotRVol	Total volume of RUSLE sand delivered to the network in year 1	River Network
iBedAgg	Initial aggradation in the riverbed from hillslope and debris flow inputs	River Network
aBedAgg	Adjusted bed aggradation of river-floodplain exchange	River Network
iPercDBF	Percentage of initial sediment input from debris flow sources	River Network
iPercRUSLE	Percentage of initial sediment input from hillslope erosion (RUSLE)	River Network
aPercDBF	Percentage of adjusted sediment input to the river from debris flow sources after river-floodplain exchange	River Network
aPercRUSLE	Percentage of adjusted sediment input to the river from RUSLE sources after river-floodplain exchange	River Network
percSand	Percent of RUSLE input that is sand	River Network, Sub-Catchments, Interfluves
RVolXyr	Volume of RUSLE sediment eroded for year X (X = 1 to 6, representing post-fire recovery years)	River Network, Sub-Catchments, Interfluves
RDVolXyr	Volume of RUSLE sediment delivered to the river for year X (X = 1 to 6)	River Network, Sub-Catchments, Interfluves

2.4.2.2 Debris Flow Probability

The Debris Flow Probability tool estimates the probability of post-wildfire debris flow initiation in a sub-catchment based on burn severity, topography, soil erodibility, and a user-defined 15-minute rainfall intensity. The model follows an empirical logistic regression approach (Eqn. 3, 4) developed by Staley et al. (2017).

$$\chi = -3.63 + (0.41 \cdot A_{\mathrm{mh23}} \cdot R_{i15}) + \left(0.67 \cdot \overline{\mathrm{dNBR}} \cdot R_{i15}\right) + \left(0.7 \cdot \overline{K_f} \cdot R_{i15}\right) \quad \text{Eqn. 3}$$

$$P = \frac{e^{\chi}}{1+e^{\chi}} \quad \text{Eqn. 4}$$

where, P is the probability of debris flow initiation, A_{mh23} is the proportion of the basin area that burned at moderate to high severity on slopes ≥ to 23 degrees, $\overline{\mathrm{dNBR}}$ is the sub-catchment average dNBR, $\overline{K_f}$ is the catchment average soil erodibility factor, and R_{i15} is the sub-catchment 15-minute rainfall accumulation (mm), derived by multiplying the provided 15-minute rainfall intensity (mm/hr) by the storm duration (0.25 hours).

To run this tool, users must provide a DEM, a sub-catchment shapefile, an SBS and dNBR raster, and STATSGO soil data containing soil erodibility (K-factor) values. Additionally, users specify a 15-minute rainfall intensity either as a constant value or a spatially variable raster, which represents the storm event used to evaluate debris flow probability.

The tool outputs either a new copy of the input sub-catchment file or an updated sub-catchment shapefile attributed with the computed probability of debris flow occurrence (Table 4) for the given rainfall intensity and the different parameters computed for Eqn 3.

2.4.2.3 Debris Flow Volume

The Debris Flow Volume tool estimates the volume of sediment mobilized by post-fire debris flows based on empirical relationships developed by Gartner et al. (2014). The model predicts debris flow sediment volume using a multiple linear regression equation that incorporates burn severity, watershed relief, and rainfall intensity (Eqn. 5). After computing the estimated debris flow volume, the tool checks for supply-limited conditions, ensuring that the predicted sediment volume does not exceed the available soil within the sub-catchment. If the predicted debris flow volume surpasses the available soil, the tool caps the transportable sediment volume at the available soil volume and flags the sub-catchment as supply-limited.

$$V = e^{\left(4.22+\left(0.39\cdot\sqrt{i_{15}}\right)+\left(0.36\cdot\ln(MH_{\mathrm{km}}\right)+\left(0.13\cdot\sqrt{R}\right)\right)} \quad \text{Eqn 5.}$$

where V is the estimated debris flow volume (m^3), i15 is the 15-minute rainfall intensity (mm/hr), MH_{km} is the upstream area burned at moderate-to-high severity (km^2), and R is the sub-catchment relief (m).

Users must provide the tool with a sub-catchment shapefile, a STATSGO soil dataset (with soil thickness information), an SBS raster, and a 15-minute rainfall intensity raster or constant value.

The tool outputs either a new copy of the input sub-catchment file or an updated sub-catchment shapefile attributed required fields to run the computations, the estimated eroded volumes, and if the resulting volumes are supply limited (Table 4).

2.4.2.4 Debris Flow Delivery

The Debris Flow Delivery tool predicts how much of the eroded debris flow sediment enters the river network using the geometric model developed by Murphy et al. (2019). First, the tool calculates the debris flow fan geometry based on valley bottom morphology and the volume of sediment entering the valley bottom. It then determines the fraction of sediment deposited within the valley bottom versus the portion that is delivered to the river network following the empirical relationships in Murphy et al. (2019). Additionally, this tool introduces a new sediment routing component that determines whether excess debris flow sediment overwhelms valley storage capacity. If the valley bottom fills, the tool propagates a sediment wedge downstream and dynamically adjusts wedge width based on river width, simulating a downstream sediment pulse in response to extreme debris flow events.

To run this tool, users must provide a sub-catchment shapefile, a sub-catchment pour points shapefile, flow direction and flow accumulation rasters, a river channel mask, and a river network shapefile attributed with bankfull river depth and width, valley bottom width, and river slope. If the modeling domain contains lakes or reservoirs, an optional reservoir shapefile can be included to account for sediment trapping. Users must also define a base name for output files and specify a temporary directory for storing intermediate calculations. Additionally, users have the option to adjust the fan splay angle (determines the spread of sediment deposition) or runout scalar fitting parameters (multiplier that adjusts predicted debris flow runout distance). The default values for these parameters are based on field observations reported in Murphy et al.

(2019). The tool allows users to optionally export updated sub-catchments and river network files with new debris flow sediment attributes. If output files are not specified, the tool directly updates the provided input datasets.

The Debris Flow Delivery tool outputs attributes (Table 4) that describe the delivery scenario used, the computed debris flow runout lengths, and the total volume of sediment delivered to the river network. If downstream sediment routing occurred, the tool also provides the local sediment delivery volume at each river reach and the amount of sediment transported further downstream. The downstream-delivered sediment is also attributed with its source sub-catchments, along with the percentage of total sediment volume each sub-catchment contributed to the receiving river segment.

2.4.2.5 Post-Fire RUSLE Yearly

Hillslope erosion can also contribute significant sediment loads following wildfire (McGuire et al., 2024). The Post-Fire RUSLE Yearly tool estimates annual sediment production using the Revised Universal Soil Loss Equation (RUSLE), modified for post-fire conditions as outlined by Gannon et al. (2019). This tool has been expanded to account for temporal post-fire recovery by adjusting erosion rates over six years, assuming a return to background erosion conditions. The model applies a linear interpolation of fire-related erosion scalars over time to reflect vegetation recovery. Additionally, this version incorporates soil bulk density to return sediment loss estimates in cubic meters (m^3) rather than the standard tons per hectare (t/ha), providing more relevant outputs for sediment transport modeling.

The R-factor (rainfall erosivity) in RUSLE is computed using different approaches depending on the selected erosivity analysis. For event-based rainfall, the tool models the storm’s intensity distribution using a Gaussian profile, simulating how rainfall varies over time. The McGregor et al. (1995) equation is then used to estimate the kinetic energy of rainfall per unit intensity. This energy is integrated over the storm duration to compute total storm erosivity (E). Finally, the R-factor is determined by multiplying E by the maximum rainfall intensity during the storm. Annual rainfall erosivity follows the Renard & Freimund (1994) equation, which relates mean annual precipitation (mm) to the R-factor using a power-law function. Alternatively, users can also provide a precomputed R-factor raster, bypassing internal calculations.

To run this tool, users must provide a DEM, flow direction and accumulation rasters, a watershed shapefile, a soil burn severity (SBS) raster, and a land cover dataset. Additionally, users need to input a STATSGO soil dataset attributed with soil erodibility (K-factor), soil thickness, bulk density, and percent sand content. Users must specify the erosivity analysis type, selecting between event-based rainfall (e.g., 15-minute intensity), annual rainfall, or an R-factor raster. If event-based rainfall is selected, the user must specify the rainfall duration (in minutes). The tool can compute outputs for entire watersheds or restrict calculations to burned areas using an optional boolean setting. Outputs include sub-catchment and interfluve shapefiles or updates to the input shapefile (Table 4), providing annual estimates of erosion and sediment delivery to the river network that decrease over time to reflect post-fire vegetation recovery.

2.4.2.6 Calculate Upstream Moderate-High Burned Area

Post-fire hydrology is influenced by the extent of burned area upstream of river segments. The Upstream Burned Area Calculator determines the fraction of each river segment's upstream drainage area that was burned at moderate-to-high severity.

To run this tool, users must provide a DEM, a river network shapefile, a network nodes file, and an SBS raster. Users must also define an output field name, which will be added to the river network attribute table, as well as specify a temporary directory and output basename for intermediate datasets. The tool outputs a river network shapefile with an added attribute indicating the fraction of upstream drainage area burned at moderate-to-high severity (Table 4).

2.4.2.7 Prepare NST

The Prepare NST tool processes spatial datasets to generate input files for the Network Sediment Transporter (NST). This tool ensures that the outputs from Infra-WEST are properly formatted and attributed for NST simulations. Additionally, the tool includes an optional river-floodplain exchange mechanism, which prevents excessive in-channel sediment accumulation by redistributing a portion of deposited sediment onto the adjacent floodplain. If activated, this function transfers sediment laterally once deposition exceeds a user-defined fraction of bankfull depth, helping to maintain channel continuity and realistic sediment storage in river channels.

To run this tool, users must provide shapefiles for interfluves, sub-catchments, and the river network, along with their respective pour point shapefiles to establish connectivity with the river network. The river network must be attributed with bankfull width and depth, valley bottom width, and segment length. Users may also specify an identifier for reservoir and lake locations to distinguish areas of potential sediment retention in the fluvial network. The tool outputs an NST-ready river network shapefile, ensuring that all attributes required for NST simulations are available.

2.5 Summary

In this section, we introduced the UDOT Post-Wildfire Geohazard Assessment Toolkit, a GIS-based Python toolkit developed to evaluate post-fire erosion and sedimentation hazards and their potential impacts on transportation infrastructure. The toolkit consists of a set of Python-based geospatial analysis tools that have an easy-to-use familiar ArcGIS GUI that can be executed individually or as part of a structured workflow. The toolkit supports two primary assessments. 1) Direct Post-Fire Geohazard Assessment which evaluates debris flow hazards along transportation corridors by calculating 15-minute rainfall intensities needed to trigger debris flows and estimating eroded sediment volumes. 2) Downstream Post-Fire Geohazard Assessment which estimates sediment volumes mobilized by debris flows and hillslope erosion, then computes the amount of sediment delivered to river networks. The outputs from this analysis are optimized for integration into 1-D sediment transport models, such as NST, which simulates sediment transport to infrastructure locations (e.g., bridges, culverts, reservoirs).

3.0 Data Acquisition and Parameterization

3.1 Overview

This section describes the data sources and model inputs used for post-wildfire geohazard assessments. The Batch Extract Tool automates the retrieval of most datasets, including topography, precipitation, land cover, and soil properties, while burn severity data is acquired separately from federal sources. Additional manually generated inputs required include transportation-river intersection points and valley bottom delineations. This section also outlines the Network Sediment Transporter (NST) model, which simulates sediment transport through river networks.

3.2 Data for Post-Wildfire Geohazard Assessment Toolkit Simulations

3.2.1 Automated Input Extraction

Inputs for the Post-Wildfire Geohazard Assessment Toolkit were primarily generated using the Batch Extract Tool, which extracts precompiled geospatial datasets for Utah. Running this tool automatically retrieves all the necessary inputs for an area of interest (AOI) specified by the user. AOI shapefiles can be created in ArcGIS Pro using a polygon that fully encompasses the desired study area, ensuring it has a set projection that will be used to project all data extracted.

The Batch Extract Tool automatically extracts the datasets listed in Table 1, including topography, land cover, precipitation data, and soil properties estimates for the state of Utah.

3.2.2 Acquiring Burn Severity Data

For Emergency Response Assessments, post-wildfire burn severity data is typically obtained from federal fire severity mapping programs, such as Burned Area Emergency Response (BAER) and Monitoring Trends in Burn Severity (MTBS). BAER teams produce burn severity assessments shortly after a wildfire is contained, providing rapid-response data for immediate hazard evaluations. In contrast, MTBS generates long-term burn severity datasets, which are not available as quickly. Both BAER (https://burnseverity.cr.usgs.gov/products/baer) and MTBS (https://www.mtbs.gov/) provide user-friendly download portals for accessing these datasets. For the simulations in this study, we utilized burn severity data derived from MTBS.

Table 5. List of all datasets that were automatically extracted using the Batch Extract Tool

Dataset Name	Description	Source
Annual Precipitation	Statewide annual precipitation raster	PRISM Climate Group
Landcover	Land cover classification dataset	National Land Cover Database
15-minute precipitation Intensity	15-minute precipitation intensity rasters for multiple return periods	NOAA Atlas 14
Primary Roads	Major road network data	TIGER (Census Bureau)
STATSGO Soil Data	Soil properties including erodibility, percent sand, thickness, and bulk density	STATSGO
DEM	Digital Elevation Model (DEM)	USGS

3.2.3 Manually Generated Inputs

For the Downstream Impacts assessment, three additional inputs must be provided beyond those generated by the Batch Extract Tool: 1) Transportation-River Intersection Points, 2) Valley Bottom Delineations, and 3) River Centerline. The transportation-river intersection points were manually mapped using aerial imagery in ArcGIS Pro. While an automated approach using the Intersect tool could extract these points, manual mapping ensures greater precision, as flow accumulation-based river delineations do not always align perfectly with transportation datasets. The valley bottom delineations and river centerlines were generated using the Fluvial Corridor Toolbox (Roux et al., 2015).

For the Direct Impacts assessment, all required inputs are automatically extracted by the Batch Extract Tool. However, if users wish to analyze a specific transportation corridor, they may need to filter out extraneous roads from the Primary Roads dataset to focus on relevant infrastructure.

3.3 Network Sediment Transporter Model Parameterization

The Network Sediment Transporter (NST) is a Lagrangian-based sediment transport model developed in MATLAB (Czuba, 2018) that simulates sediment movement through river networks at daily timesteps. NST represents sediment as discrete parcels transported downstream based on local hydraulic conditions, allowing for the explicit tracking of sediment. The model applies a mixed grain-size transport function (Wilcock & Crowe, 2003), which accounts for grain-size-dependent transport capacity. NST operates under unsteady flow conditions and dynamically updates bed elevation to simulate aggradation and erosion processes. However, it does not simulate lateral channel migration or bank erosion, assuming static channel width throughout the simulation. NST has been applied in post-wildfire sediment routing studies (Murphy et al., 2019) and serves as a framework for watershed-scale sediment transport modeling. The modeling framework applied here follows a similar approach to Murphy et al. (2019) but incorporates additional refinements, including RUSLE-based hillslope sediment inputs and improved flow scaling methods.

NST requires several key inputs beyond those provided by the Geo-Hazards Toolkit, including debris flow grain-size distributions, initial bed grain-size estimates, and hydrologic data. Debris flow sediment grain sizes were assigned based on the 25th and 75th percentiles of measured debris flow sediment distributions from field studies on the Twitchell Fire (Murphy et al., 2019). Hillslope erosion inputs were partitioned into two classes: 1) Sand-sized sediment, which is explicitly tracked in NST and, 2) Finer than sand, which is assumed to be washload and not explicitly modeled. Initial bed grain sizes for the river network were estimated using the Snyder et al. (2013) grain-size prediction model.

The hydrologic inputs for NST consist of post-wildfire discharge hydrographs at daily timesteps, generated using historical streamflow data from hydrologically similar basins. The process begins by selecting representative water years based on flow exceedance probabilities, ensuring that low and high flow conditions are captured. These hydrographs are then scaled to reflect post-fire hydrology using empirical multipliers that account for increased flow due to watershed burn severity. Additionally, post-wildfire flow scaling is only done for rainfall runoff events and not for snowmelt driven flow (Canham et al., 2024), consistent with field observations. The resulting scaled hydrographs are propagated through the watershed using regional regression equations, which estimate reach-specific discharge based on drainage area. The final hydrologic dataset provides post-fire daily discharge values for NST sediment transport simulations across each geohydrologic region (Kenney et al., 2007) in Utah.

NST does not simulate floodplain dynamics, meaning all simulated sediment remains within the main river channel. To prevent artificially high shear stress calculations, discharges exceeding the 2-year flow recurrence interval are thresholded at this level. This approach reflects the reality that once rivers enter flood stage, further increases in discharge result in minimal additional shear stress within the channel. By applying this threshold, NST avoids overestimating sediment transport under extreme flow conditions, ensuring that model outputs remain physically realistic.

4.0 Model Simulations and Results

4.1 Overview

This section demonstrates the applicability of the geospatial toolkit in predicting post-wildfire sedimentation hazards. To evaluate potential risks, we used a bookended approach, simulating both low and high hazard conditions. The geospatial hazard models were run with a 2-year rainfall event for the low scenario and a 25-year rainfall event for the high scenario.

For all geospatial simulations, we set the probability threshold for debris flow occurrence to 50%, meaning any sub-catchment with a debris flow probability of 50% or greater was assumed to generate a debris flow, consistent with standard USGS practice (Staley et al., 2017). This threshold was also applied in the Direct Impact tools to determine the required triggering rainfall intensity.

Post-Fire RUSLE simulations were conducted for both burned and unburned sub-catchments and interfluves, using an annual rainfall raster to assess erosivity. In unburned sub-catchments, the model represents background erosion rates since post-wildfire scaling factors are not applied. Additionally, RUSLE was run within debris flow-generating sub-catchments, as debris flows occur at the event scale and do not remove all sediment. This allows for continued hillslope erosion in these areas over time.

NST simulations incorporated different grain size distributions and hydrologic conditions for each hazard scenario. The low hazard scenario used a coarser debris flow grain size distribution (75th percentile) and a low-flow hydrologic scenario (25th percentile water year). In contrast, the high hazard scenario used a finer grain size distribution (25th percentile) and a high-flow hydrologic scenario (75th percentile water year). These simulations provide a comparative framework for assessing sediment hazards under a range of post-wildfire conditions.

4.2 State Route 143 (Brian Head Fire, near Parowan, UT)

4.2.1 Model Setup

We modeled post-fire hazards from the Brian Head Fire along SR 143 (Figure 1). The Brian Head Fire burned 74,276 acres near Parowan, Utah, spanning two watersheds crossed by SR 143. For the downstream impacts analysis, we specified two pour points to delineate each watershed. In the eastern watershed, an additional pour point was placed at the lake outlet to support a nested basin analysis. However, since there is no road–river crossings within the nested basin, we excluded it from the downstream impacts analysis. All crossings downstream of the fire perimeter were manually delineated (Figure 1). For the direct impacts analysis, sub-catchments were delineated directly from SR 143 adjacent to the fire parameter (Figures 1 and 2).

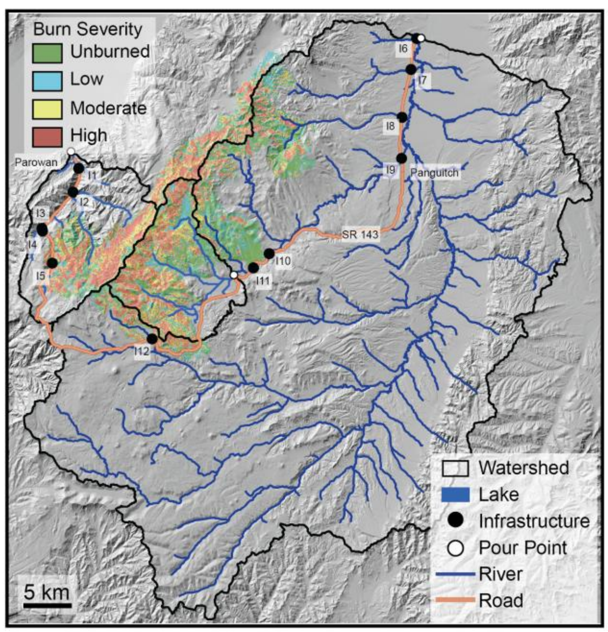

Figure 1. Study area for the State Road 143 site showing the watershed extent, lakes/reservoirs, transportation corridor, pour points and infrastructure locations, delineated river network, and soil burn severity within the fire perimeter.

4.2.2 Direct Impacts Results

The Direct Impacts tools were used to evaluate debris flow hazards from sub-catchments draining directly to the SR 143 corridor. Figure 2 summarizes two key model outputs: the 15-minute rainfall intensity required to trigger a debris flow for 50% probability (Figure 2A) of the debris flow occurring, and the estimated sediment volume generated if triggered (Figure 2B). Areas with lower intensity thresholds and moderate to high eroded volumes may represent locations with elevated potential for post-fire impacts to roads and culverts. For example, one sub-catchment on the western portion of the corridor is predicted to produce between 10,000–50,000 m^3 of sediment in response to storms with intensities of 20–30 mm/hr (Figure 2). Additional moderate-hazard catchments are located throughout the corridor, highlighting areas of concern if large storms had occurred.

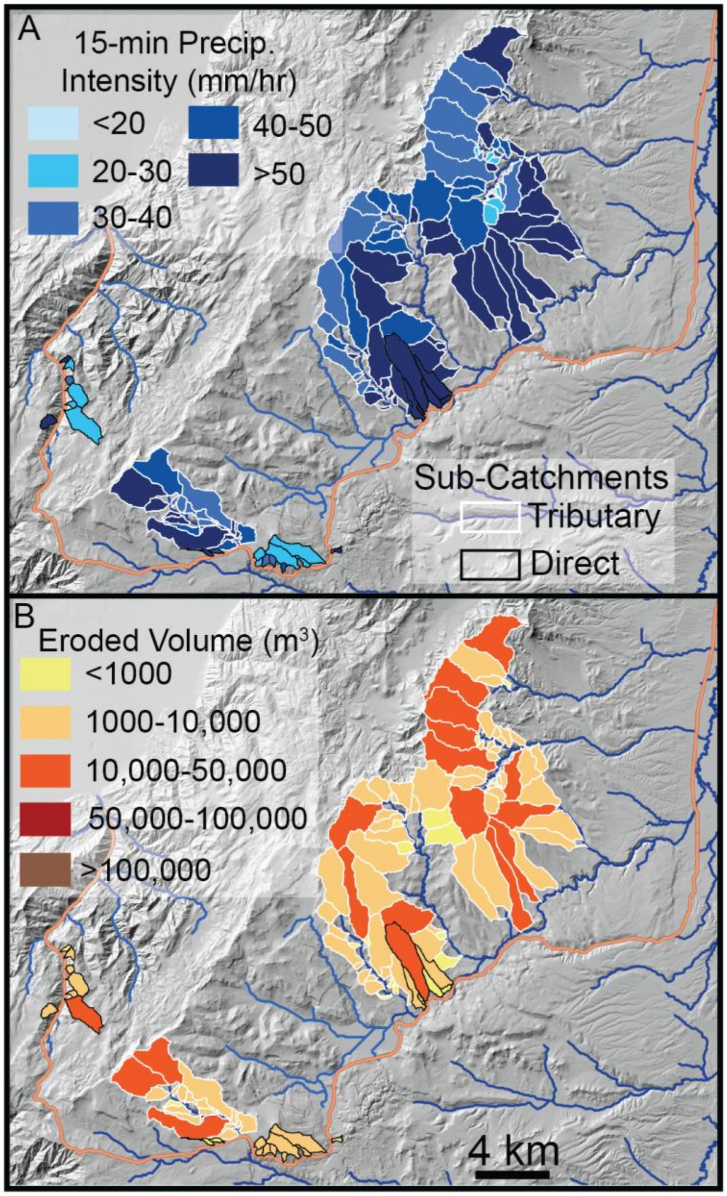

Figure 2. Results of the Direct Impacts analysis for SR 143. (A) Rainfall intensity (mm/hr) required to trigger debris flows at 50% probability based on the Staley et al. (2017) model. (B) Estimated debris flow sediment volumes for each direct sub-catchment based on the Gartner et al. (2014) model. Together, these maps highlight areas with both high susceptibility and high potential impact following the Brian Head Fire.

4.2.3 Downstream Impacts

Infra-USUAL identified 1,741 sub-catchments within the SR 143 watersheds, of which 171 (9.8%) burned during the Brian Head Fire. Under the 2-year rainfall scenario, 92 burned sub-catchments (53.8%) were predicted to have at least a 50% probability of generating a debris flow, while all 171 burned sub-catchments (100%) exceeded this threshold under the 25-year scenario (Figure 3 A–B). Total estimated debris flow sediment volumes were 1,226,911 m^3 eroded and 175,164 m^3 delivered to the river network under the 2-year rainfall scenario, increasing to 5,261,276 m^3 eroded and 1,739,721 m^3 delivered under the 25-year scenario (Figure 3 C–F). RUSLE-based hillslope erosion was estimated at 3,844,867 m^3 in the first year post-fire (Figure 4A), with 175,255 m^3 of that volume delivered to the river network (Figure 4B) and an additional 971,995 m^3 delivered over the subsequent 9 years.

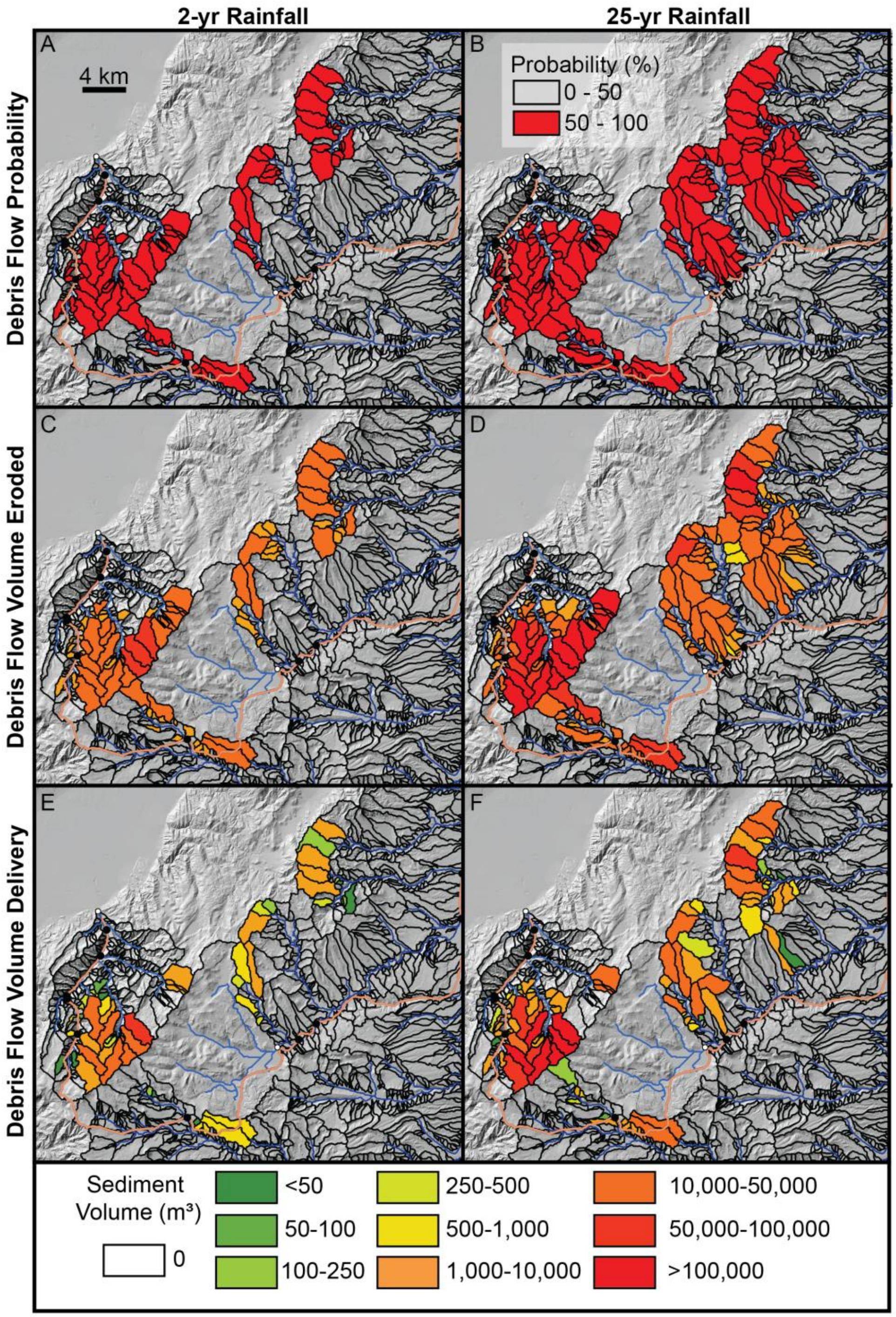

Figure 3. Debris flow hazard estimates for SR 143 under two rainfall scenarios. Panels A, C, and E show results for the 2-year rainfall scenario, while panels B, D, and F show results for the 25-year scenario. Panels A and B display debris flow probability (%), C and D show estimated

debris flow volumes eroded (m^3), and E and F show estimated debris flow volumes delivered (m^3) to the river network.

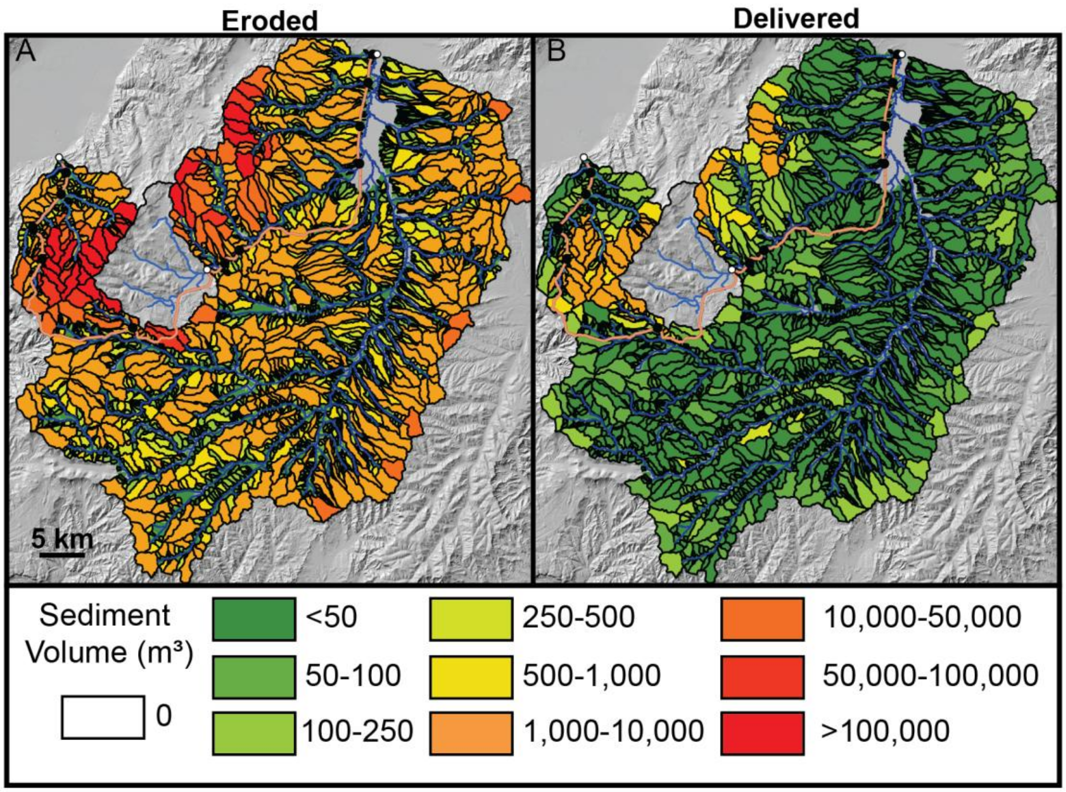

Figure 4. Year-1 SR-143 RUSLE results. Maps showing estimated hillslope erosion (m^3) (A) and sediment delivery (m^3) to the river network (B) during the first year following the Brian Head Fire.

Cumulative sediment flux estimates at each infrastructure location indicate that sediment delivery is front-loaded, with the majority of sediment arriving within the first 1–3 years post-fire (Figure 5). Under the high sediment supply scenario, several culverts (e.g., I1, and I2) received over 600,000 m³ of sediment by the end of the simulation, with steep delivery curves in the first year and smaller pulses in subsequent years (Figure 5 B, D). Culvert I6 showed a more delayed response, with a secondary increase in sediment flux occurring after year 3.5, suggesting the arrival of sediment from more distal sources farther upstream.

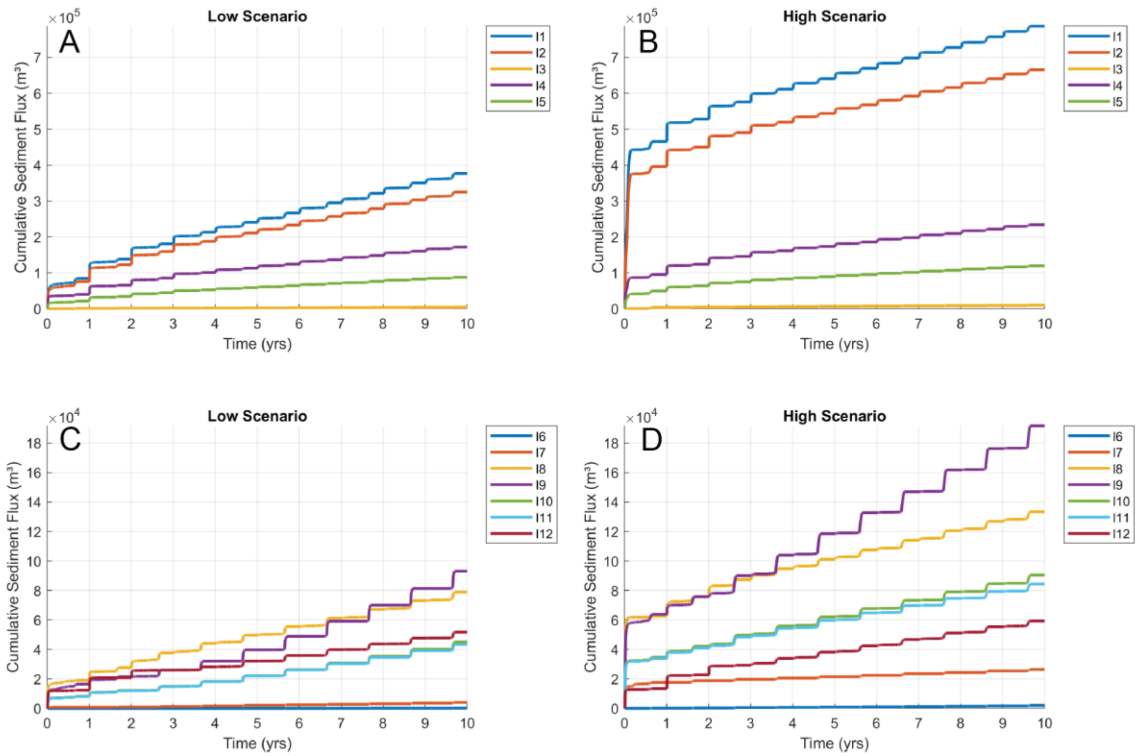

Figure 5. Modeled cumulative sediment flux to infrastructure crossings on SR 143. (A–B) Crossings I1–I5. (C–D) Crossings I6–I12. Panels show low (left) and high (right) scenarios.

4.3 U.S. Route 89/6 (Pole Creek Fire, near Spanish Fork, UT)

4.3.1 Model Setup

We modeled post-fire sedimentation hazards from the Pole Creek Fire along US 89 and US 6 (Figure 6). The Pole Creek Fire burned 102,426 acres near Spanish Fork, Utah, and intersected a single watershed draining toward the Spanish Fork River corridor. For the downstream impacts analysis, one pour point was specified near Spanish Fork (Figure 6) to capture all contributing drainage areas. Road–river crossings along US 89 and US 6 downstream of the fire were manually delineated (Figure 6). For the direct impacts analysis, sub-catchments were delineated from US 89 and US 6 at locations adjacent to the burn perimeter (Figures 6 and 7).

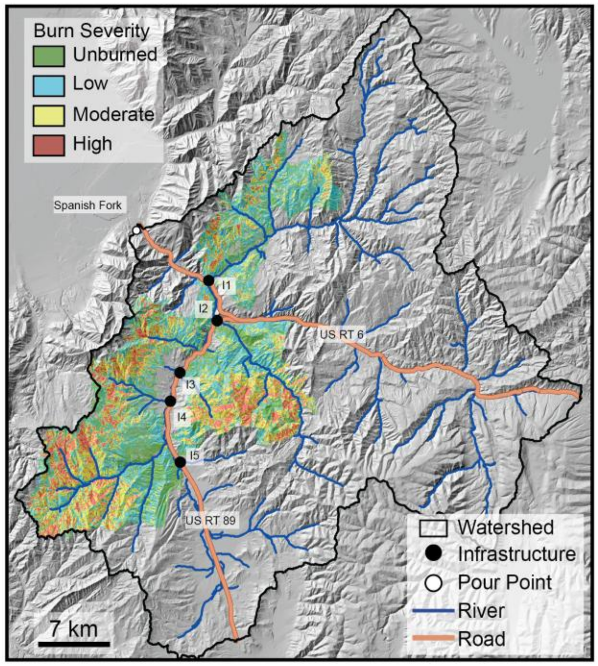

Figure 6. Study area for the US Route 89 and 6 site showing the watershed extent, transportation corridor, pour points and infrastructure locations, delineated river network, and soil burn severity within the fire perimeter

<u>4.3.2 Direct Impacts Results</u>

The Direct Impacts tools were used to evaluate debris flow hazards from sub-catchments draining directly to US 89 and US 6. Figure 7 shows two key components of this analysis: the 15-minute rainfall intensity required to trigger a debris flow with at least 50% probability (Figure 7A), and the estimated debris flow volume from each sub-catchment (Figure 7B). Debris flow modeling suggests a concentration of high-hazard sub-catchments near the center of the burn area, where multiple tributaries drain steep, severely burned slopes. Several locations adjacent to US 89 exhibit moderate to high sediment volumes paired with low rainfall thresholds (20–30 mm/hr), indicating elevated vulnerability to even relatively small post-fire storms.

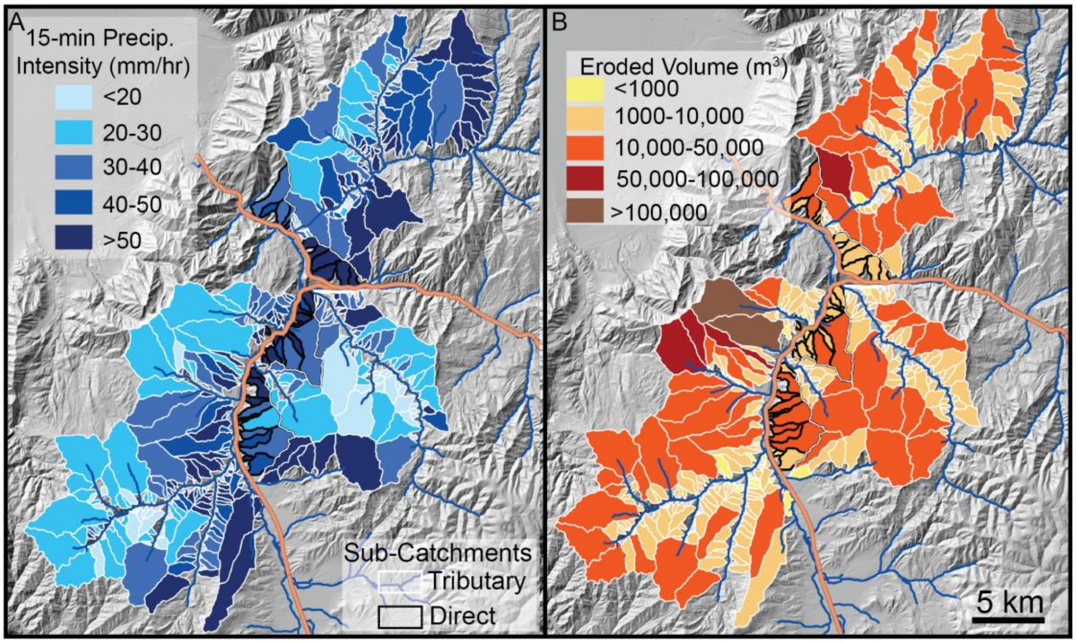

Figure 7. Results of the Direct Impacts analysis for the US 89/6 site. (A) Rainfall intensity (mm/hr) required to trigger debris flows at 50% probability based on the Staley et al. (2017) model. (B) Estimated debris flow sediment volumes for each sub-catchment based on the Gartner et al. (2014) model.

4.3.3 Downstream Impacts

Infra-USUAL identified 1,451 sub-catchments within the US 89/6 watershed, of which 482 (33.2%) burned during the Pole Creek Fire. Under the 2-year rainfall scenario, 221 of the burned sub-catchments (45.8%) exceeded the 50% probability threshold for debris flow initiation, increasing to 472 sub-catchments (98%) under the 25-year scenario (Figure 8 A–B). Estimated debris flow sediment volumes totaled 2,596,876m^3 eroded and 478,894 m^3 delivered to the river network under the 2-year rainfall scenario, increasing to 10,329,084 m^3 eroded and 3,484,040 m^3 delivered under the 25-year scenario (Figure 8 C–F). RUSLE-based hillslope erosion was estimated at 21,157,599 m^3 in the first post-fire year (Figure 9A), with 640,811 m^3 of that volume delivered to the river network (Figure 9B). An additional 3,697,069 m^3 of RUSLE-delivered sediment was estimated over the subsequent nine years.

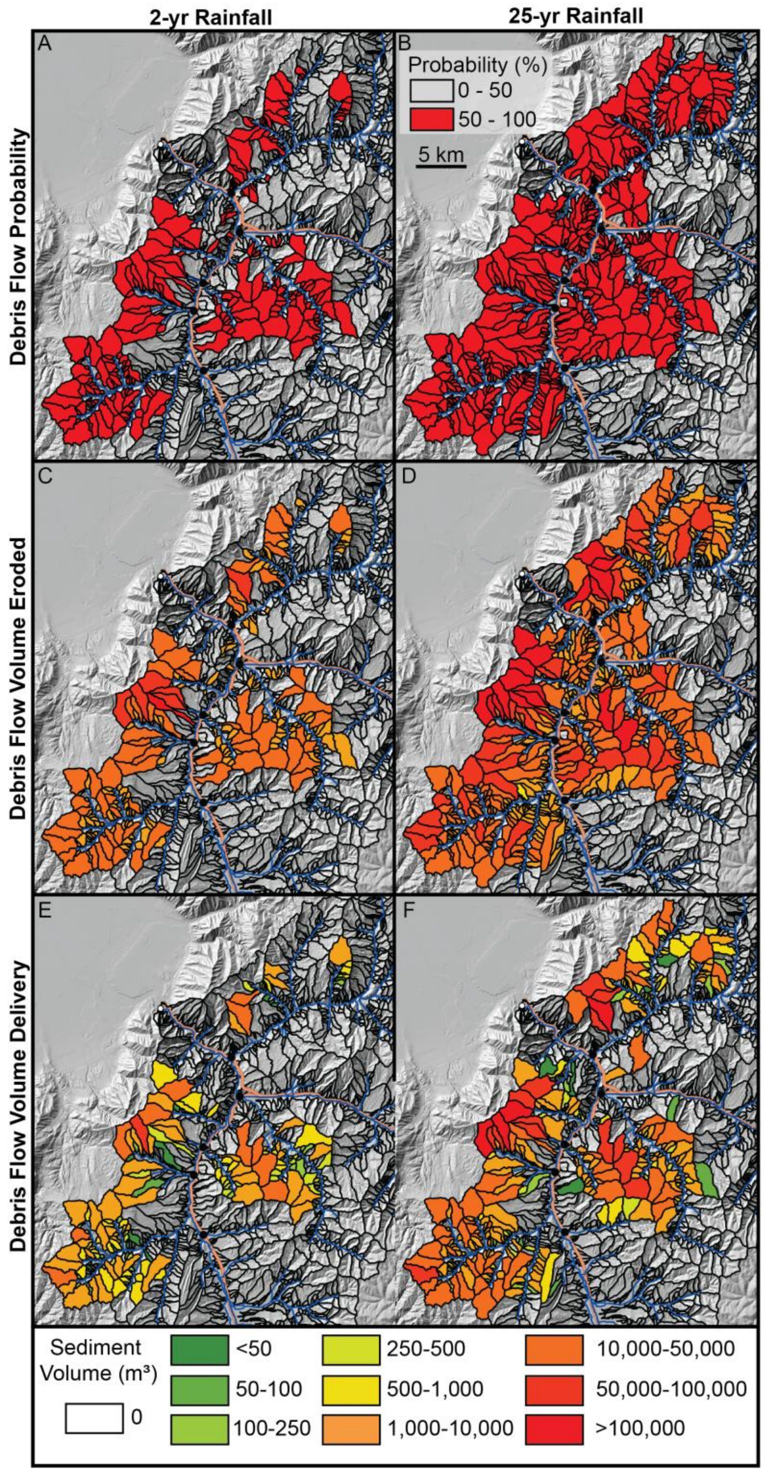

Figure 8. Debris flow hazard estimates for the US 89/6 site under two rainfall scenarios. A, D, and E panels show the 2-year rainfall scenario; B, D, and F panels show the 25-year scenario. (A–B) Debris flow probability (%). (C–D) Estimated debris flow sediment volumes eroded. (E–F) Estimated debris flow sediment volumes delivered to the river network.

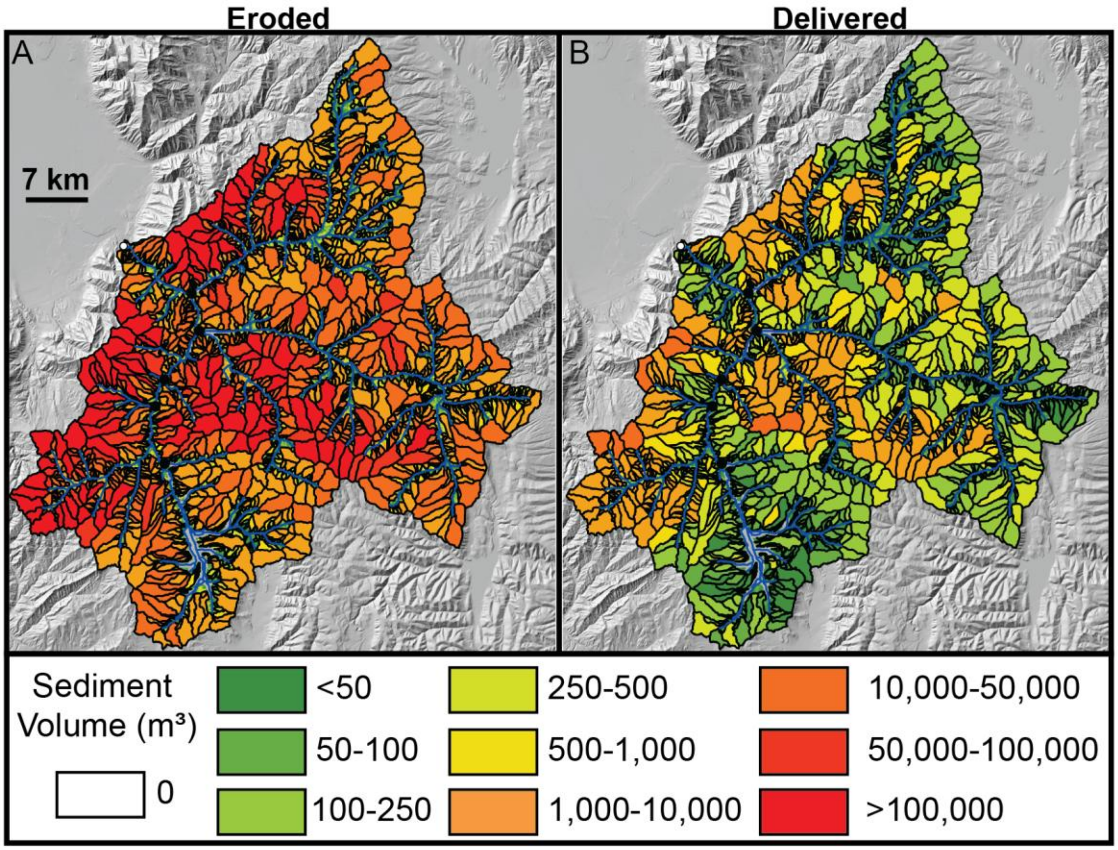

Figure 9. Year-1 RUSLE erosion results for the US 89/6 site. (A) Estimated hillslope erosion volume. (B) Estimated volume of RUSLE-derived sediment delivered to the river network.

The NST routing model simulated post-fire sediment transport from both debris flows and RUSLE-based hillslope erosion. Figure 10 shows the cumulative sediment flux reaching each infrastructure location under both the low and high scenarios. Under the high rainfall scenario, a large pulse of sediment was routed in the first year following the fire, particularly at I1, I2, and I4. Fluxes at I5 and I3 were notably lower, consistent with smaller upstream contributing areas and reduced sediment inputs. By year three, the rate of sediment flux at most locations began to slow, but sediment delivery continued at a more uniform, lower rate through year ten.

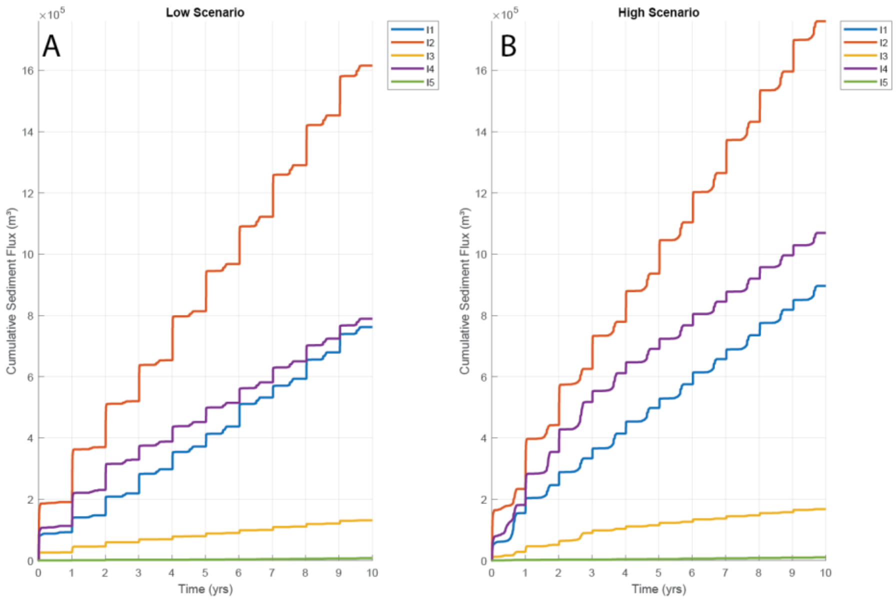

Figure 10. Modeled cumulative sediment flux to infrastructure crossings on US 89 and US 6. Panels show low (A) and high (B) scenarios.

4.4 State Route 40 (Dollar Ridge Fire, near Duchesne, UT)

4.4.1 Model Setup

We modeled post-fire hazards from the Dollar Ridge Fire along State Route 40 (Figure 11). The Dollar Ridge Fire burned 68,817 acres near Duchesne, Utah. For the downstream impacts analysis, two pour points were placed: one at the upstream extent near Strawberry Reservoir and another downstream at Starvation Reservoir. The nested analysis allowed us to separate out sediment contributions above Strawberry Reservoir, which is expected to trap incoming sediment. Infrastructure crossings along SR 40 downstream of the fire perimeter were manually delineated for the sediment routing analysis. For the direct impacts analysis, sub-catchments were delineated from SR 40 along the corridor adjacent to the fire perimeter (Figures 11 and 12).

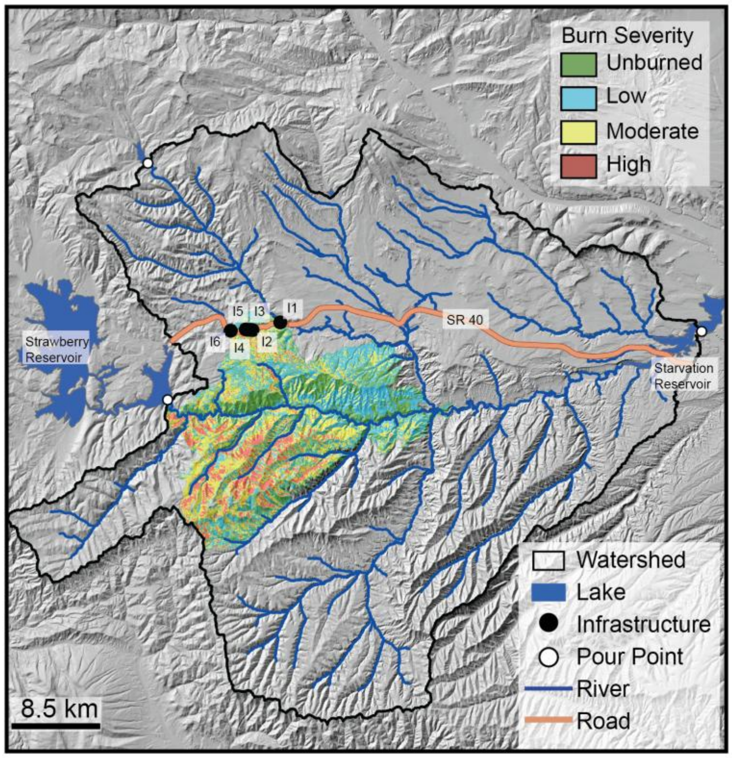

Figure 11. Study area for the State Route 40 site showing the watershed extent, lakes/reservoirs, transportation corridor, pour point and infrastructure locations, delineated river network, and soil burn severity within the fire perimeter.

4.4.2 Direct Impacts Results

The Direct Impacts tools were used to evaluate debris flow hazards from sub-catchments draining directly to the SR 40 corridor. Figure 12 summarizes two key model outputs: the 15-minute rainfall intensity required to trigger a debris flow for 50% probability (Figure 12A) and the estimated sediment volume generated if triggered (Figure 12B). Much of the corridor shows low to moderate rainfall thresholds (20–40 mm/hr) for debris flow triggering. Several sub-catchments south of the corridor are predicted to generate between 10,000 and 50,000 m^3 of sediment. These locations may pose elevated post-fire hazards to roads and culverts if intense summer thunderstorms had occurred.

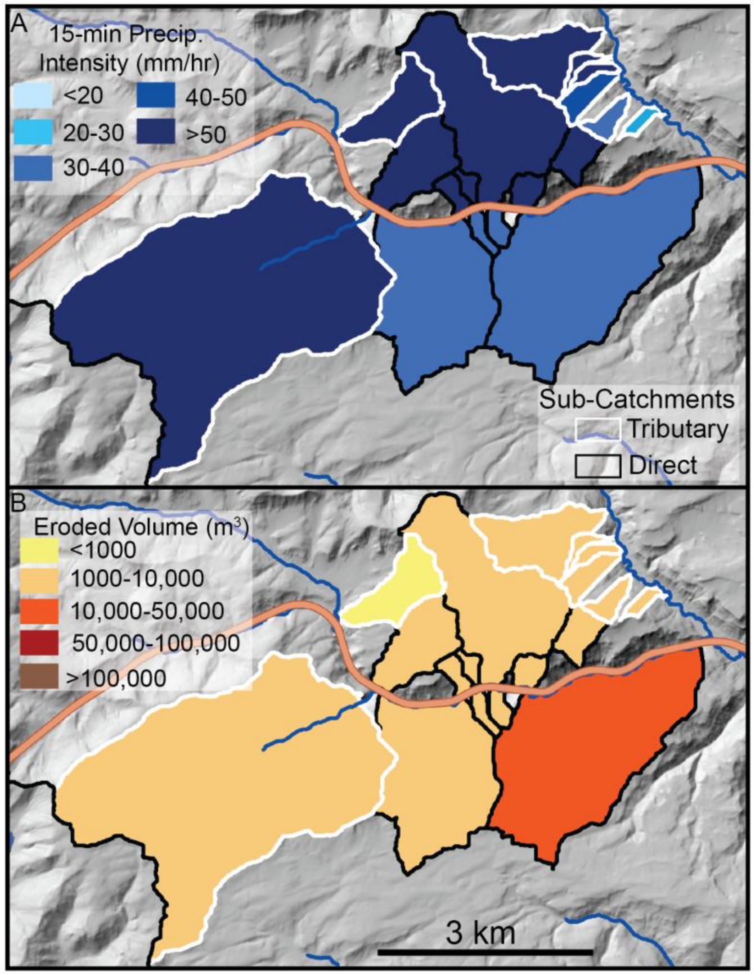

Figure 12. Results of the Direct Impacts analysis for SR 40. (A) Rainfall intensity (mm/hr) required to trigger debris flows at 50% probability based on the Staley et al. (2017) model. (B) Estimated debris flow sediment volumes for each direct sub-catchment based on the Gartner et al. (2014) model.

4.4.3 Downstream Impacts

Infra-USUAL identified 1,798 sub-catchments within the contributing watershed to SR 40, of which 315 (17.5%) burned during the Dollar Ridge Fire. Under the 2-year rainfall scenario, 117 burned sub-catchments (37.1%) were predicted to have at least a 50% probability of generating a debris flow, increasing to 81.9% (258 sub-catchments) under the 25-year scenario (Figure 13 A–B). Total estimated debris flow sediment volumes were 985,578 m³ eroded and 147,583 m³ delivered to the river network under the 2-year rainfall scenario, increasing to 4,550,630 m^3 eroded and 1,048,331 m^3 delivered under the 25-year scenario (Figure 13 C–F). RUSLE-based hillslope erosion in the first post-fire year was estimated at 12,266,057 m^3 (Figure 14A), with 476,437 m^3 of that volume delivered to the river network (Figure 14B). Over the subsequent 9 years, an additional 2,679,188 m^3 of sediment was estimated to be delivered via hillslope erosion.

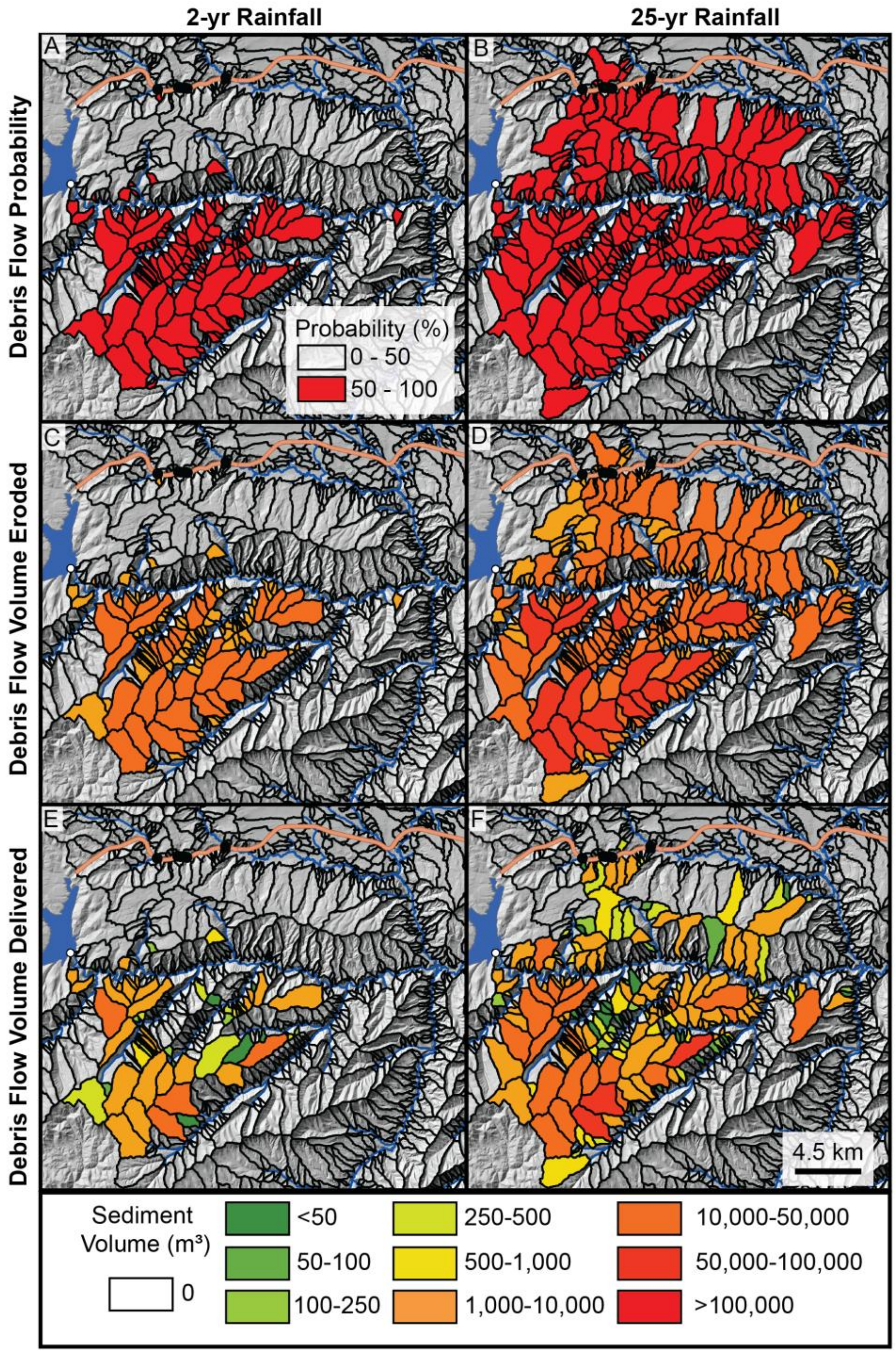

Figure 13. Debris flow hazard estimates for SR 40 under two rainfall scenarios. Panels A, C, and E show results for the 2-year rainfall scenario, while panels B, D, and F show results for the 25-year scenario. Panels A and B display debris flow probability (%), C and D show estimated debris flow volumes eroded (m^3), and E and F show estimated debris flow volumes delivered (m^3) to the river network.

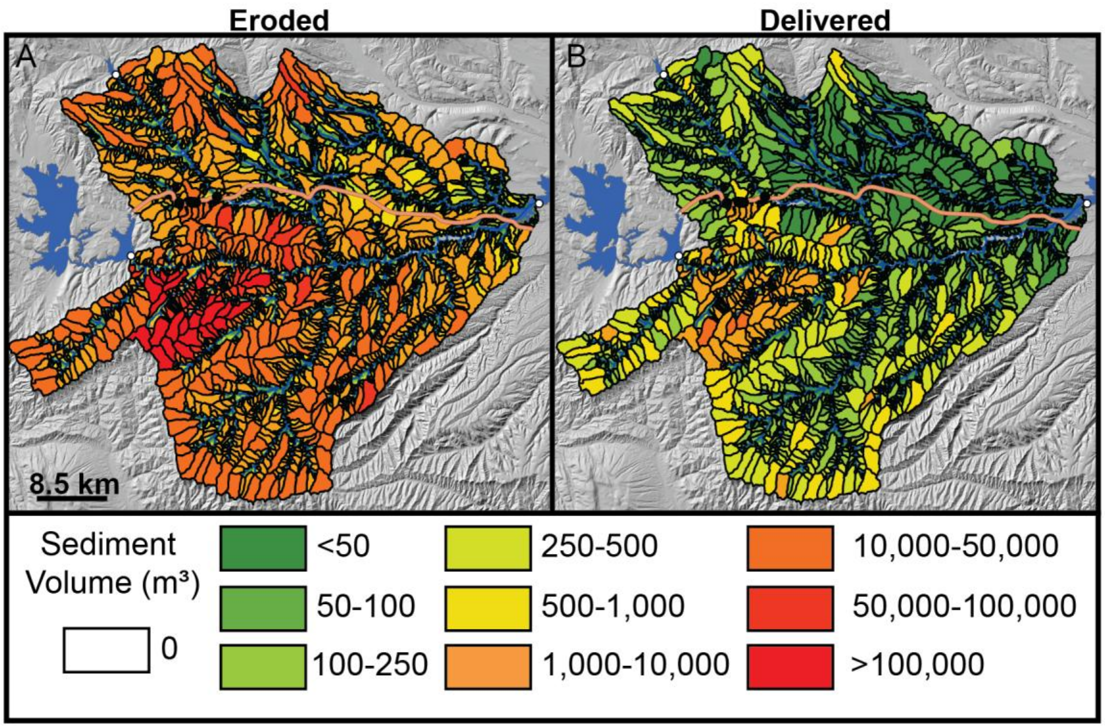

Figure 14. Year-1 SR 40 RUSLE results. Maps showing estimated hillslope erosion (m^3) (A) and sediment delivery (m^3) to the river network (B) during the first year following the Dollar Ridge Fire.

Modeled cumulative sediment flux to infrastructure crossings along SR 40 (Figure 15) shows a relatively steady rise for most culverts. Under the high flow scenario, crossing I1 contributed over 250,000 m^3 of sediment, while all other crossings remained below 50,000 m^3. The steepest increase in sediment flux for most bridges and culverts occurred approximately two years into the simulation.

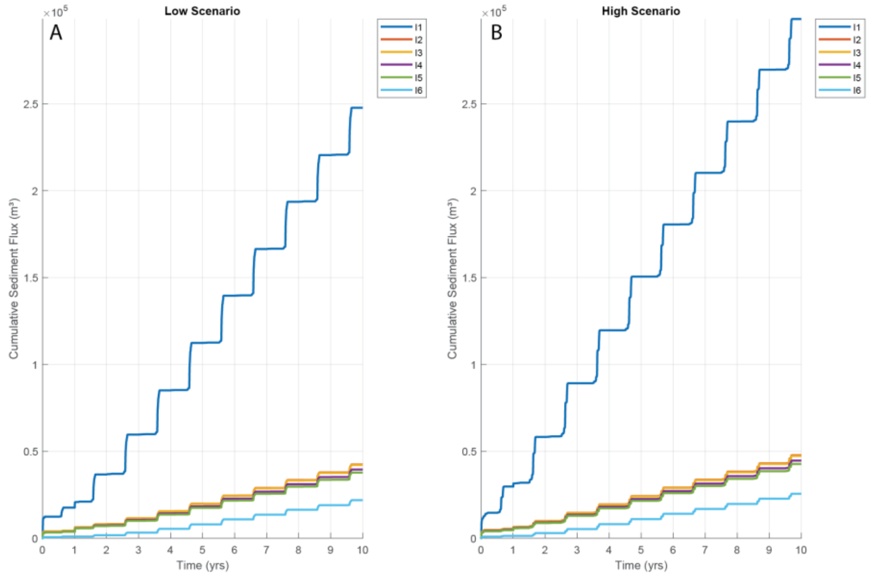

Figure 15. Modeled cumulative sediment flux to infrastructure crossings on SR 40. (A–B) Crossings I1–I6. Panels show low (left) and high (right) flow scenarios.

4.5 U.S. Route 6 (Bear Fire, near Helper, UT)

4.5.1 Model Setup

We modeled post-fire hazards from the Bear Fire along U.S. Route 6 (Figure 16). The Bear Fire burned 12,660 acres near Helper, Utah. For the downstream impacts analysis, a single pour point was specified to delineate the contributing watershed. A small reservoir in the eastern corner was excluded from the analysis through a nested basin delineation to isolate its influence. Infrastructure crossings along US 6 downstream of the fire perimeter were manually delineated for sediment routing analysis. For the direct impacts analysis, sub-catchments were delineated directly from US 6 adjacent to the fire perimeter (Figures 16 and 17).

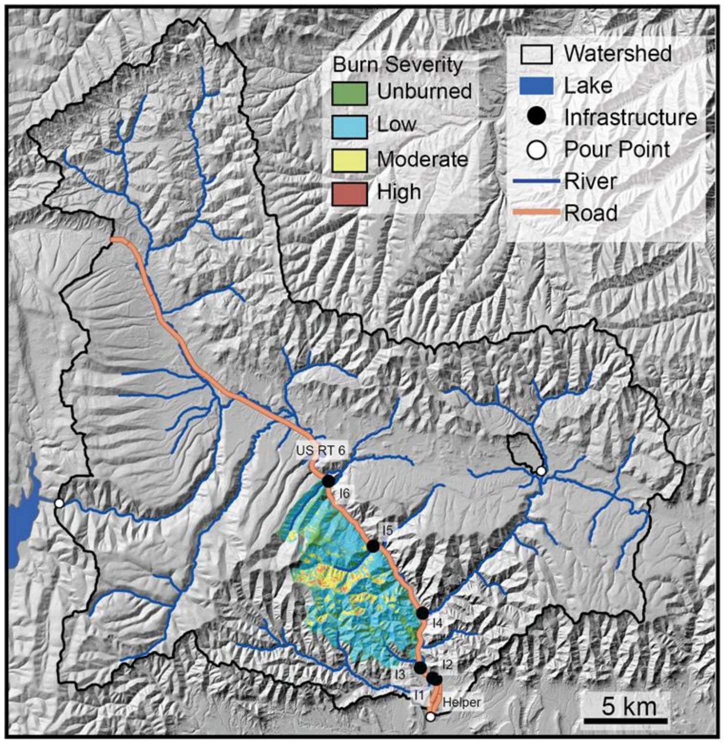

Figure 16. Study area for the U.S. Route 6 site showing the watershed extent, transportation corridor, pour point and infrastructure locations, delineated river network, and soil burn severity within the fire perimeter.

4.5.2 Direct Impacts Results

The Direct Impacts tools were used to evaluate debris flow hazards from sub-catchments draining directly to the US 6 corridor. Figure 17 summarizes two key model outputs: the 15-minute rainfall intensity required to trigger a debris flow with 50% probability (Figure 17A) and the estimated sediment volume generated if triggered (Figure 17B). Notably, the sub-catchment in Crandall Canyon exhibits the lowest rainfall intensity threshold for debris flow initiation, indicating high susceptibility to post-fire debris flows. This finding aligns with observed post-fire sediment delivery events that impacted US 6 in this area.

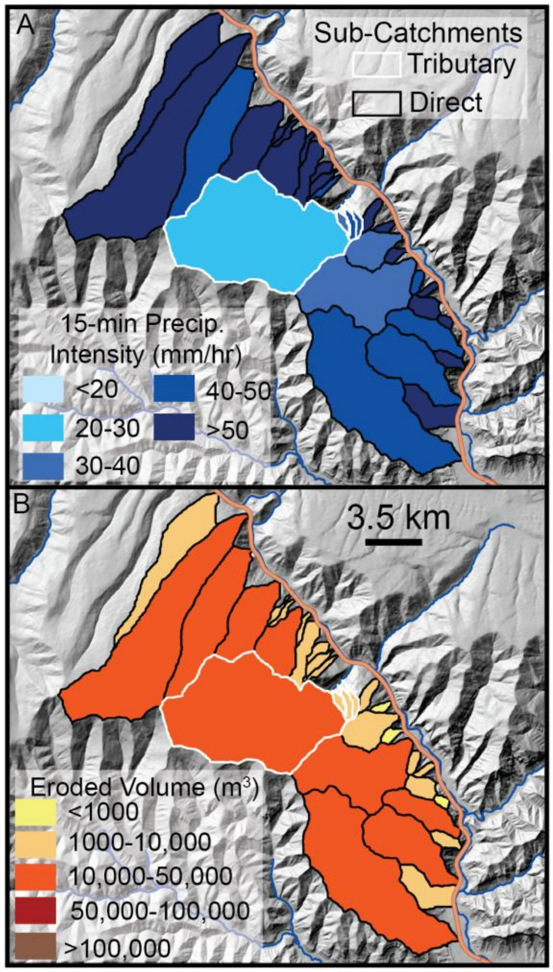

Figure 17. Results of the Direct Impacts analysis for US 6. (A) Rainfall intensity (mm/hr) required to trigger debris flows at 50% probability based on the Staley et al. (2017) model. (B) Estimated debris flow sediment volumes for each direct sub-catchment based on the Gartner et al. (2014) model.

4.5.3 Downstream Impacts

Infra-USUAL identified 689 sub-catchments within the contributing watershed to US 6, of which 68 (9.9%) burned during the Bear Fire. Under the 2-year rainfall scenario, 9 burned sub-catchments, all located in Crandall Canyon, (13.2%) were predicted to have at least a 50% probability of generating a debris flow, increasing to 66 sub-catchments (97.1%) under the 25-year scenario (Figure 18 A–B). Total estimated debris flow sediment volumes were 76,843 m^3 eroded and 2,527 m^3 delivered to the river network under the 2-year rainfall scenario, increasing to 767,310 m³ eroded and 127,933 m³ delivered under the 25-year scenario (Figure 18 C–F). RUSLE-based hillslope erosion in the first post-fire year was estimated at 2,851,344 m³ (Figure 19A), with 94,776 m³ of that volume delivered to the river network (Figure 19B). Over the subsequent 9 years, an additional 829,448 m³ of sediment was estimated to be delivered via hillslope erosion, reflecting continued sediment contributions from burned slopes.

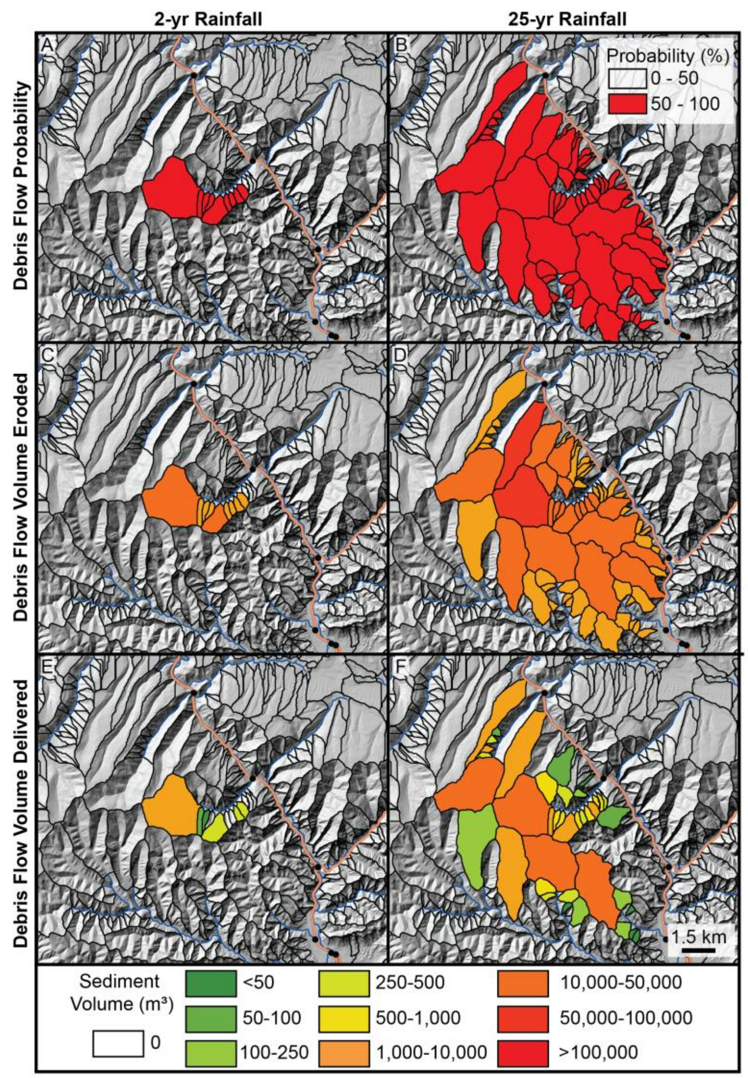

Figure 18. Debris flow hazard estimates for US 6 under two rainfall scenarios. Panels A, C, and E show results for the 2-year rainfall scenario, while panels B, D, and F show results for the 25-year scenario. Panels A and B display debris flow probability (%), C and D show estimated

debris flow volumes eroded (m³), and E and F show estimated debris flow volumes delivered (m³) to the river network.

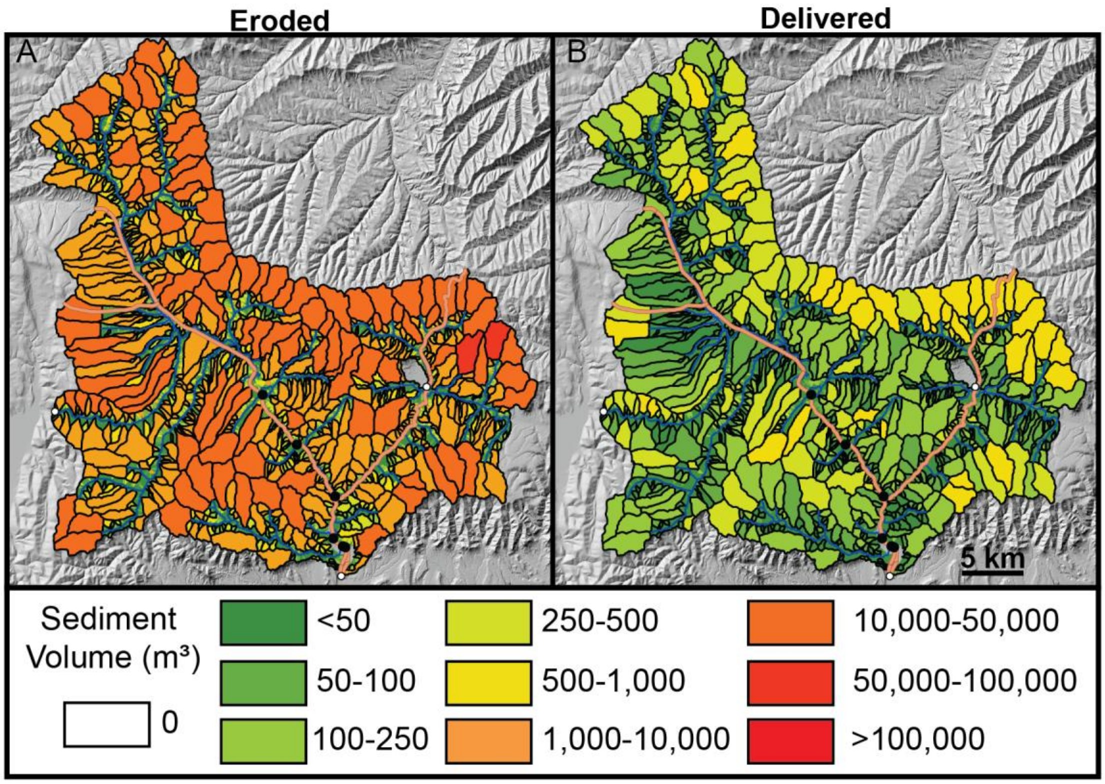

Figure 19. Year-1 US 6 RUSLE results. Maps showing estimated hillslope erosion (m³) (A) and sediment delivery (m³) to the river network (B) during the first year following the Bear Fire.

Modeled cumulative sediment flux to infrastructure crossings along US 6 (Figure 20) indicates that sediment delivery is predominantly front-loaded, with the majority of sediment arriving within the first 1–2 years post-fire. Under the high sediment supply scenario, crossings such as I1, and I4 received over 1,500,000 m³ of sediment by the end of the simulation, with steep delivery curves in the first year and more gradual accumulation in later years. In contrast, I2, I3, I4 and I6 received substantially less sediment, reflecting differences in contributing area and sediment supply.

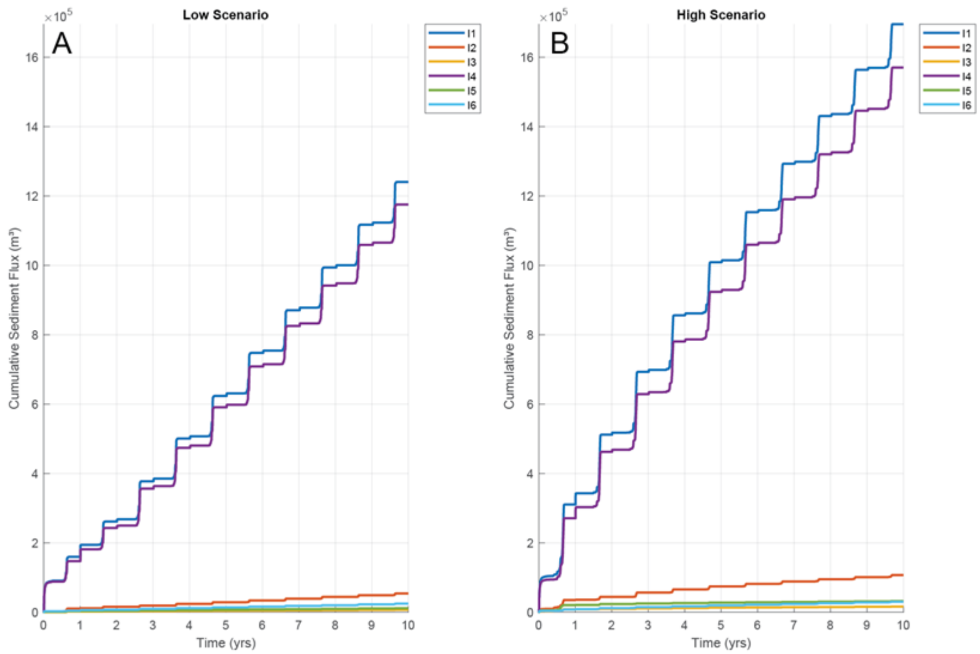

Figure 20. Modeled cumulative sediment flux to infrastructure crossings on US 6. (A–B) Crossings I1–I6. Panels show low (left) and high (right) flow scenarios.

4.6 State Route 196 (Big Springs Fire, near Tooele, UT)

4.6.1 Model Setup

We modeled post-fire hazards from the Big Springs Fire along State Route 196 (Figure 21). The Big Springs Fire burned a relatively small area (2,958 acres) southwest of Tooele, Utah. Given the lack of major road–river crossings downstream of the fire perimeter, only the Direct Impacts tools were used for this location. Sub-catchments were delineated along SR 196 adjacent to the fire perimeter to assess debris flow potential and sediment volumes (Figures 21 and 22).

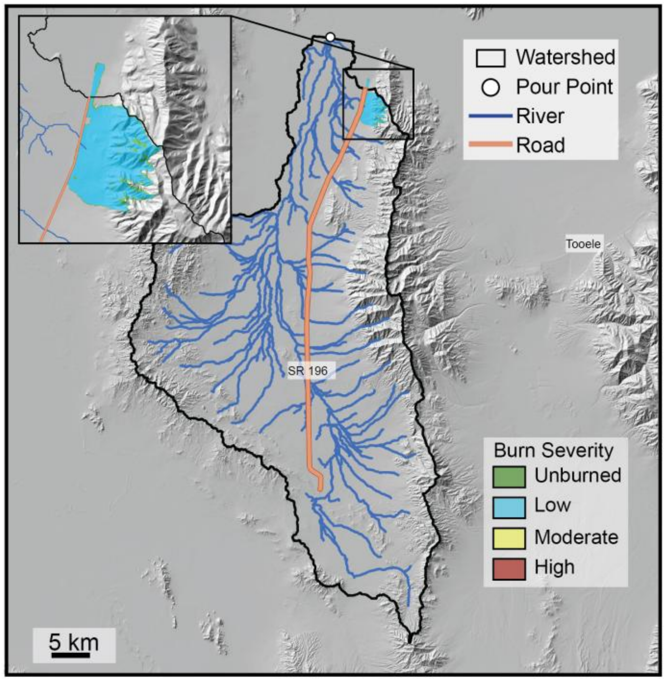

Figure 21. Study area for the State Route 196 site showing the transportation corridor, delineated watershed and river network, and soil burn severity within the fire perimeter.

4.6.2 Direct Impacts Results

Figure 2 summarizes the predicted debris flow hazards along SR 196 based on rainfall intensity and sediment volume models. The majority of sub-catchments required relatively high rainfall intensities (>30 mm/hr) to trigger debris flows with 50% probability (Figure 2A), and most were estimated to produce less than 10,000 m³ of sediment (Figure 2B). These results suggest limited post-fire risk to infrastructure along SR 196, given the fire's low burn severity and small spatial extent.

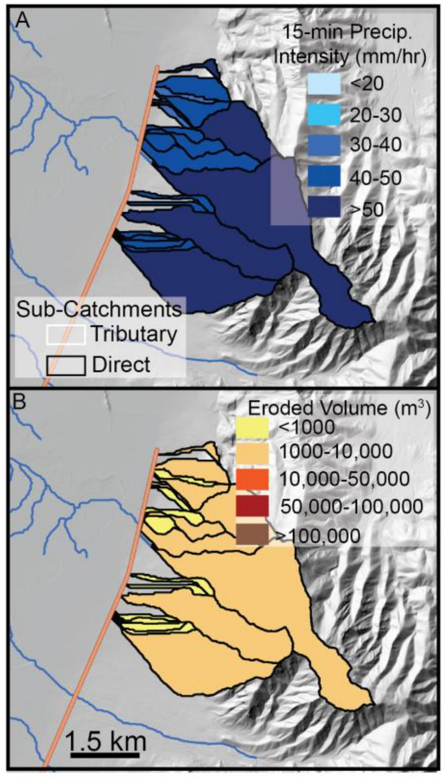

Figure 22. Results of the Direct Impacts analysis for SR 196. (A) Rainfall intensity (mm/hr) required to trigger debris flows at 50% probability based on the Staley et al. (2017) model. (B) Estimated debris flow sediment volumes for each direct sub-catchment based on the Gartner et al. (2014) model.

5.0 CONCLUSIONS

5.1 Summary and Findings

Wildfires are increasing in frequency and severity across the western United States, posing significant risks to transportation infrastructure due to post-wildfire erosion and sedimentation hazards. To support transportation planners in addressing these risks, we introduce the UDOT Post-Wildfire Geohazard Assessment Toolkit, a GIS-based framework designed to evaluate post-wildfire sedimentation hazards and their potential impacts on roads, bridges, and culverts. The toolkit integrates precompiled geospatial datasets with user-supplied burn severity data to estimate debris flow probability, sediment erosion, and sediment delivery to river networks from both hillslope erosion and debris flows. To demonstrate its functionality, we applied the toolkit to five case study locations in Utah, showcasing its ability to rapidly assess post-fire geohazards. A companion report (UT-25.13) details the application of this toolkit for proactive planning, enabling transportation agencies to anticipate and mitigate sedimentation hazards before a wildfire occurs.

Across the five case study sites, the toolkit successfully identified high-risk locations for post-wildfire sediment impacts, demonstrating its effectiveness in providing actionable hazard assessments. The Direct Geohazard Impact Tools efficiently evaluated debris flow probability and sediment volumes along transportation corridors, enhancing existing hazard assessment methodologies with transportation-specific analyses. The Downstream Impact Tools quantified post-wildfire erosion and sediment delivery to river networks, generating outputs that integrate seamlessly with 1-D watershed-scale sediment transport models, such as the Network Sediment Transporter (NST), to assess sediment delivery to in-stream transportation infrastructure. By automating data extraction and analysis workflows, the toolkit significantly reduces the time and expertise required for hazard assessments, making it a valuable resource for transportation agencies responding to wildfire emergencies.

5.2 Limitations and Challenges

While the UDOT Post-Wildfire Geohazard Assessment Toolkit provides a powerful framework for assessing post-fire sediment hazards, several key limitations should be considered. One major limitation is related to hydrologic assumptions. The toolkit relies on selecting flow percentiles to represent future post-fire hydrologic conditions. The current approach does not account for nonstationary hydrologic conditions or long-term changes due to climate or land use shifts. While the bookend approach used in this study (e.g., selecting upper and lower bound flow conditions) helps account for some uncertainty, users could refine analyses by running additional simulations to explore a broader range of flow conditions. Another limitation is the assumed grain-size distributions of debris flow sediment. The current approach assigns debris flow grain sizes based on field observations. However, grain-size distributions should vary across watersheds with different characteristics (e.g., lithology, slope, and soil permeability). Improved models for predicting post-fire debris flow grain-size distributions would enhance these estimates and reduce the need to treat grain size as a scenario-based parameter.

The model also assumes static channel geometry, relying on regression equations to estimate river dimensions. However, post-wildfire sedimentation and hydrologic changes can cause channel widening, bank erosion, and shifts from single-thread to multi-threaded channel forms, which are not currently accounted for in NST simulations. Future improvements should aim to incorporate dynamic channel morphology adjustments.

Another key limitation is the simplified representation of long-term landscape recovery. The model assumes a linear recovery trajectory over six years for hillslope erosion and that all debris flows occur within the first post-fire year. In reality, vegetation regrowth, soil stabilization, and sediment delivery processes evolve non-linearly, meaning that further refinement of recovery dynamics is needed. Additionally, debris flow fans can continue contributing sediment to the river for years following the fire, however we currently lack a robust model to quantify these inputs.

A further limitation is the reliance on remotely sensed burn severity data when field-validated Soil Burn Severity (SBS) rasters are not available. The toolkit uses classified BARC

(Burned Area Reflectance Classification) maps as a proxy for SBS, but these maps may not accurately represent on-the-ground soil conditions. In the absence of a federal BAER team response, SBS data are typically not produced, limiting the accuracy of erosion and sediment modeling in these cases. This limitation is particularly relevant for fires occurring on non-federal lands or areas not managed by agencies with BAER authority, such as USDA Forest Service or DOI land management agencies.

Additionally, the model does not incorporate culvert capacities, meaning it cannot determine when culverts or bridges are at risk of failure due to sediment clogging. It also assumes that no upstream sediment is trapped by culverts or bridges, which could lead to overestimations of sediment transport in some cases. Further, the model does not account for woody debris, which can trap sediment at infrastructure locations. These feedbacks may increase the risk of localized sediment deposition and infrastructure damage. These limitations highlight key areas for future research and development to improve the predictive accuracy of post-wildfire sediment hazard assessments.

While a key outcome of this study is an easy-to-use geospatial toolkit for assessing wildfire sedimentation impacts to transportation corridors, the tools are designed with a streamlined GUI that allows GIS users to operate them without writing code or building custom workflows. This structure improves accessibility for anyone comfortable using GIS software and requires no programming experience. However, it is essential that users understand the underlying models and assumptions to ensure that input parameters are applied correctly and results are interpreted appropriately. The ease of running the models does not guarantee meaningful results, particularly when users deviate from default values without a solid understanding of the tool's logic. In such cases, the models may still execute successfully, but the outputs could be invalid or misleading. Thus, while the toolkit simplifies execution, responsible and informed use is necessary.

Finally, the models integrated into this toolkit, including empirical equations for debris flow probability and volume, hillslope erosion predictions, sediment routing routines, and geometric delivery models, have each been independently developed and validated in prior research. However, a formal sensitivity analysis of the linked framework has not yet been performed. Based on prior work and implementation experience, key sensitivities are expected to include burn severity classification accuracy, assumed post-fire flow magnitude, and debris flow grain-size inputs. A comprehensive sensitivity analysis is a logical next step to help users prioritize data quality and identify which inputs most strongly influence model outcomes. As this is the first comprehensive framework of its kind for post-wildfire sediment hazard assessment in transportation corridors, a system-wide sensitivity analysis and formal validation are key next steps that can be undertaken as additional field data become available.

5.3 Toolkit and Data Access

The UDOT Post-Wildfire Geohazard Assessment Toolkit, including the user manual, tutorial videos, and precompiled datasets, can be accessed at https://usu.box.com/s/2x89ntse9tmb4ig8zaw7vs4ynzk6gcyt. Efforts are underway to publish the toolkit in peer-reviewed journals to ensure broad accessibility. Upon publication, the tools will be hosted at https://github.com/WatershedsWildfireResearchCollaborative where they will be maintained and updated to ensure compatibility with future versions of ArcGIS Pro.

6.0 RECOMMENDATIONS AND IMPLEMENTATION

6.1 Recommendations and Implementations

We recommend that the UDOT Post-Wildfire Geospatial Assessment Toolkit be run following any wildfire that occurs adjacent to transportation infrastructure. The toolkit can be implemented as soon as remotely sensed burn severity products (e.g., dNBR or Soil Burn Severity maps) become available. Running the toolkit early in the post-fire timeline allows UDOT to assess potential debris flow and sedimentation hazards before the first significant rainfall events.

These results can support short-term decisions such as issuing debris flow hazard warnings and prioritizing field inspections of vulnerable culverts and road segments. The outputs can also inform coordination with landowners, land managers, and partner agencies (e.g., U.S. Forest Service) to evaluate and implement appropriate mitigation strategies, such as constructing sediment retention basins or deploying erosion control. Integrating the toolkit into UDOT's post-fire response workflow will improve the agency's ability to actively plan for and manage sedimentation hazards reducing risk to infrastructure and individuals travelling in the affected corridors.

Future iterations of the toolkit development may incorporate using machine learning techniques to enhance the accuracy of individual model components. While applying machine learning across the entire modeling framework is currently limited by the need for large-scale validation datasets and the complexity of the system, there is strong potential for targeted improvements within specific sub-models. For example, Random Forest or similar methods could be used to develop more accurate and regionally adapted empirical models for post-fire river discharge, debris flow volumes, and sediment grain-size distribution predictions, areas where current estimates rely on limited datasets, simplified scaling relationships, or localized field observations. In particular, while the debris flow volume model used here represents the current standard, machine learning could help refine predictions as more post-fire response data become available. Machine learning could also support scenario and site prioritization or help identify high-sensitivity input parameters. These enhancements would support more efficient and adaptive model applications while preserving transparency and scientific defensibility.

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