Modeling Post-Wildfire Flood Dynamics to Determine Urban Stormwater Infrastructure Needs: Flagstaff Arizona Case Study

Edward R. Schenk, City of Flagstaff, Arizona, Edward.schenk@flagstaffaz.gov
Joseph B. Loverich, JE Fuller Hydrology and Geomorphology, Flagstaff, Arizona, joe@jefuller.com
Allen Haden, Natural Channel Design Inc, Flagstaff, Arizona, allen@naturalchanneldesign.com

Abstract

The impacts of post-wildfire flooding on channels, floodplains, and watersheds in general have been well documented. The impact of post-wildfire flooding on the urban environment, and specifically on stormwater infrastructure, is still relatively understudying or reported. The purpose of this case study is to provide examples of stormwater infrastructure post-fire impacts and the need for proactive planning, modeling, and design to provide urban flood relief in wildfire burn scar watersheds. A case study of Flagstaff, Arizona is provided with a focus on the 2019 Museum Fire (Spruce Wash) with supporting information from the 2010 Schultz Fire (six un-named ephemeral watersheds) and 2022 Pipeline Fire (Schultz Creek) watersheds as study sites. The case study provides examples of flood events and multi-agency stormwater planning, flood modeling, and floodplain map revisions to assist in mitigating the flood threat.

Introduction

The extreme drought paired with abnormally dense forest stands in the American Southwest has created more intense and frequent wildfires (Westerling and Swetnam 2003; Littell et al. 2016). Additionally, Summer monsoons are forecasted to become more extreme in the American Southwest as climate change intensifies the atmospheric rivers coming out of the Gulf of California and Pacific Ocean (Bhattacharya et al. 2018). These two trends are greatly increasing the risk of post-wildfire flash floods in the American Southwest, at a rate undocumented in history. Post wildfire flooding at the urban-forest interface is an increasingly important issue for city and county governments to address as traditional stormwater planning, capital expenditures, and maintenance and operations are insufficient for the order of magnitude change in rainfall-runoff flow and sediment transport created by wildfire burn scars.

This paper provides a hydrological and hydraulic modeling case study that was successfully utilized for several fires in the Flagstaff, Arizona area to predict flood flows and risks for the Schultz Fire (2010), Museum Fire (2019), and Pipeline Fire (2022). These methods have successfully guided local government mitigation efforts for the Schultz and Museum Fires and are currently being used for capital improvements for the Museum and Pipeline Fires. In addition, we provide empirical observations of the validity and accuracy of these methods under these conditions. While the methods were utilized on all three fires, empirical comparisons to modeling efforts are focused on the Museum Fire in this paper for the sake of brevity. All measurement units are presented in Standard English instead of scientific units due to the applied nature of this study. A companion paper provides the sediment modeling that was developed concurrently with this flood risk study (Schenk et al. 2023).

Study Site

Flagstaff, Arizona lies at the southern edge of the dormant San Francisco Volcanic Field including the San Francisco Peaks, Dry Lake Hills, and Mount Elden. The local watersheds are generally complacent, unless disturbed, with extremely low rainfall-runoff ratios due to local geology (weathered dacite, cinders, and karstic fractured limestone), vegetation (dense *Pinus ponderosa* forest), and relatively deep soil organic layers (Leao and Tecle 2005; Schenk et al. 2021). The Spruce Wash watershed is an ephemeral tributary to the Rio de Flag, another ephemeral watershed that drains the southern portions of the San Francisco Volcanic Field. The Spruce Wash watershed drains the six dacite intrusive hills that make up the Dry Lake Hills feature as well as the western portion of Mount Elden, a larger protuberance of the same orogeny (Holm 2019; Schenk et al. 2021). A previous USGS study observed a peak flow of 5 cubic feet per second (CFS) in the Spruce Wash watershed over a period of 11 years (Hill et al. 1988) despite a watershed contributing area of greater than 5.6 square miles.

The Museum Fire occurred in July 2019 over 2000 acres of the Spruce Wash watershed on the steep, mountainous slopes of Dry Lake Hills and Mount Elden, both of which are immediately uphill of established residential areas of Coconino County (CC) and City of Flagstaff (CoF; Figure 1). Mount Elden Estates (MEE) is a rural residential area and is the uppermost residential area within the Spruce Wash Watershed. Approximately one mile downstream and separated by open USFS land are the urban residential areas of Paradise/Sunnyside, which are within the CoF city limits. MEE is located on flatter slopes near the base of Dry Lake Hills on the leading and lower edge of a previously inactive alluvial fan. Paradise/Sunnyside are on the toe of inactive alluvial fans and adjacent to the broad, ephemeral, and formerly unchannelized Spruce Wash. Prior to the Museum Fire, the Paradise/Sunnyside neighborhoods had one defined channel/pipe system and surface water flow seldom occurred within these existing channels. Up gradient on USFS land, intermittent surface flows were spread over wide alluvial fans (areas of sediment deposition) and were easily absorbed into the unconsolidated sediment. Consequently, surface water flows within the channels were primarily from stormwater runoff during normal precipitation events from local CoF streets. Stormwater infrastructure within the wash included grassed channelized ditches in the upstream portion of the neighborhoods that transitioned to a 60 inch corrugated metal pipe, all conveyances were sized to the 1% (100 year) storm event as identified by the Federal Emergency Management Agency (FEMA) flood insurance study (FEMA 2010).

The Museum Fire burned in July-August 2019 and for the duration 2019 and 2020, the Flagstaff region saw record low summer monsoonal rain with no substantial post-fire impacts. Initial flooding occurred during the above average summer monsoon season of 2021, resulting in four significant floods (July 13, 14, 16 and August 17th). Post-fire flooding resulted in vast amounts of flooding and sedimentation in downstream residential areas as existing drainage features and channels were overwhelmed with post-fire sedimentation.

Methods

Hydrologic and Hydraulic Modeling

Hydrologic and hydraulic modeling was completed using FLO-2D software. The FLO-2D version used for this study is the Pro Version Build No. 19.07.21 with an executable dated March 20, 2020 (FLO-2D Software, Inc., 2017).

FLO-2D is a conservation of volume, two-dimensional (2-D), flood routing model. The model estimates runoff from prescribed precipitation events and routes the flow (rainfall runoff) over a grid comprised of square elements based on topography (defined by grid element elevations) and watershed roughness

(Manning's n-value assigned to each grid element). This 2-D modeling approach is highly suited for simulating the distributed, unconfined flow prevalent in alluvial fan and piedmont areas below the burn scar within the study area. There is significant variability in burn severity within watersheds and that variability can be modeled effectively within FLO-2D.

In the immediate post-fire risk analysis, the model was developed with grids comprised of 20-foot square elements for fast run times and efficient risk mapping. That model was then refined to consist of 5-foot square elements with two modeling domains. Domains were defined for the "mountain" area, and the "city" area due to the number of grid elements (9,971,829 grid elements). Given the detail of the model (relatively small grid elements), significant drainage features such as channels and basins (natural and man-made) are topographically reflected. Drainage infrastructure such as storm drains and culverts are modeled to create a realistic representation of flood risk. Additional information regarding the FLO-2D software can be found at http://www.flo-2d.com/.

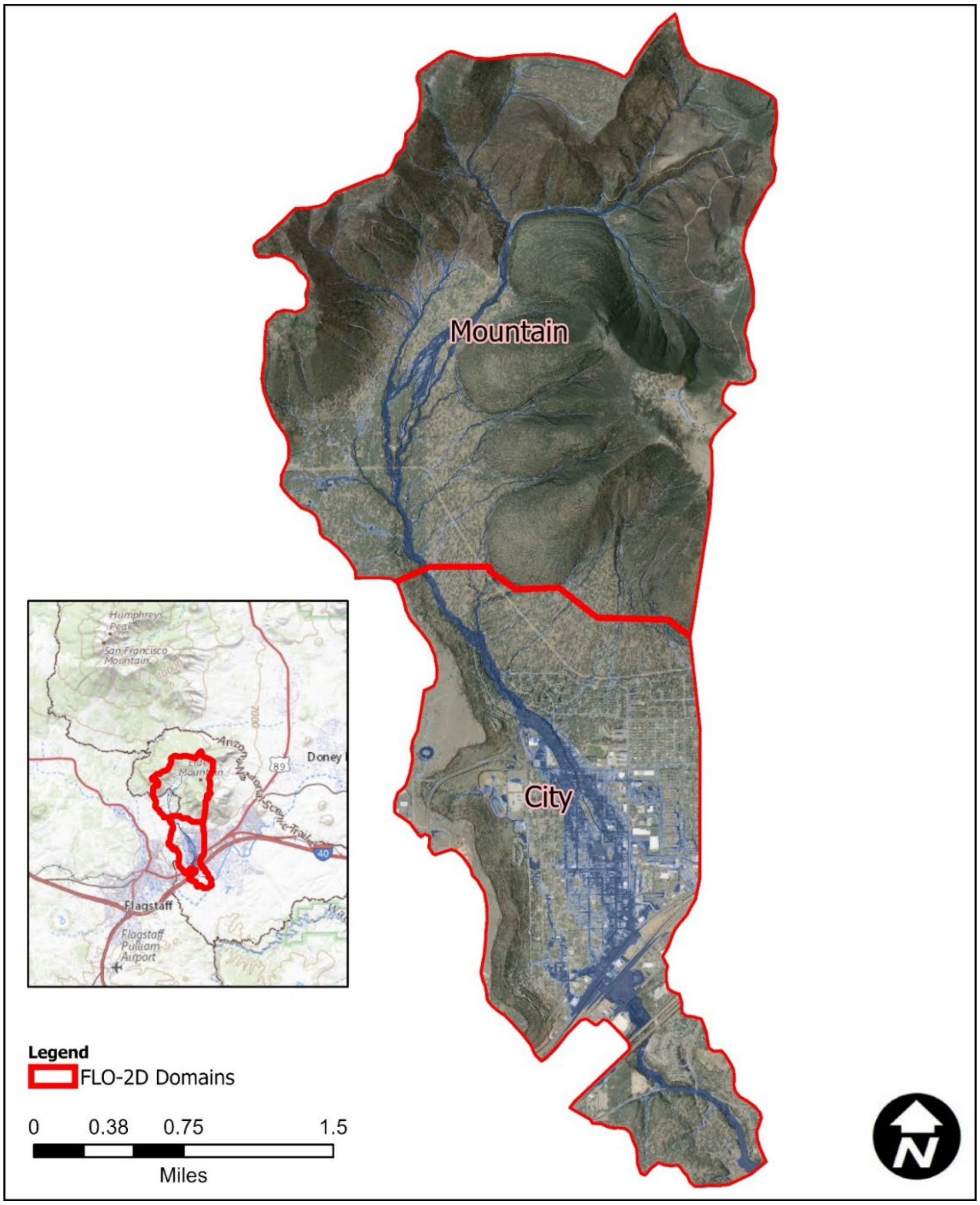


Figure 1. FLO-2D numerical modeling domain for the 2019 Museum Fire.

Elevation

The immediate post-fire modeling was completed using 2015 City of Flagstaff LiDAR data collected prior to the Museum Fire. To reflect current topography and channel geometry, new LiDAR and ortho imagery were collected in November 2021 (NV5 Geospatial, 2022) and was used in the latest iteration of models. The 2021 LiDAR data was provided with an imagery resolution of 0.5 ft and surface vertical accuracy of 1.5 cm.

Rainfall

There were two types of storms that were modeled over the watershed. Based upon inspection of prior monsoon depths, durations, and intensities in the vicinity of the study area, a highly specific and customized 45-minute storm with 1-inch, 2-inch, and 3-inch rainfall depths was modeled. The distribution used was based upon research of rainfall gage data acquired from actual storm events that occurred over the 2010 Schultz Fire. The July 20th, 2010 rainfall event that occurred in the Schultz Fire Watershed produced 1.75 inches of rain in 45 minutes and was selected as the representative distribution producing both high intensities and rainfall depths (Figure 2). Second, the 100-year, 6-hour SCS Type II event was modeled to provide a representative design storm per the City of Flagstaff Stormwater Management Design Manual (2009).

All models assume that there is rainfall over the entire watershed and FLO-2D domain.

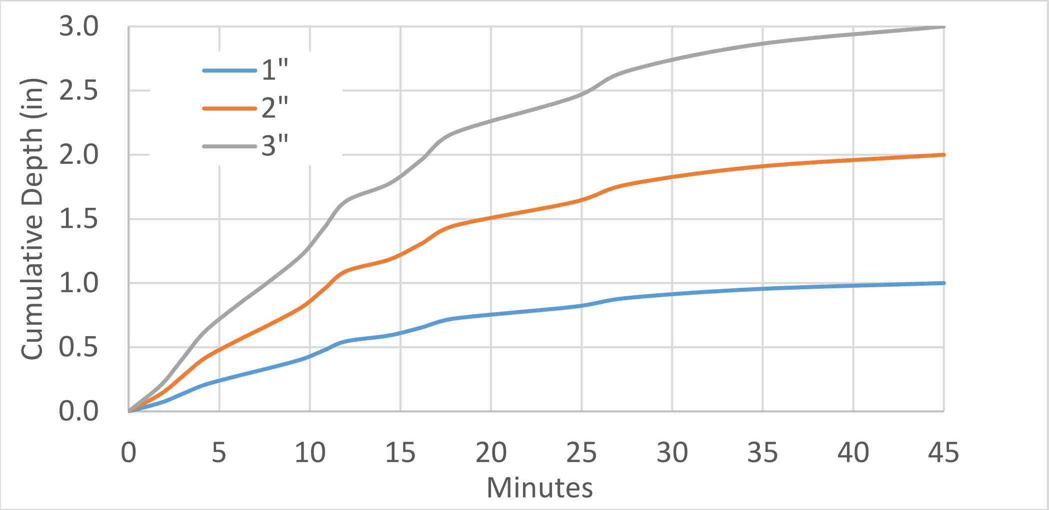


Figure 2. Design storm (45-minute) rainfall events. Cumulative depth is provided in inches.

Post-Fire Infiltration

Reduction in infiltration capacity due to vegetation loss and soil hydrophobicity are two driving factors in post-wildfire increases in runoff and erosion. Pre-fire curve numbers (CN's) were adjusted to represent post-fire conditions based on soil burn severity (SBS) data provided by the U.S. Forest Service's (USFS) Burned Area Emergency Response (BAER) Team (USDA, USFS, 2019). Burn severity values are classified as (1) Unburned, (2) Low Severity, (3) Moderate Severity, and (4) High Severity. Post-fire curve numbers (Table 1) were assigned as follows:

- Moderate and high burn severity areas: CN=94.
- Low burn severity areas: CN=71, 76 or 85 depending on type of soil/vegetation.
- Very Low/Unburn Areas: CN remains unchanged.

Curve Number adjustments were based on discussions with the USFS BAER team members and references to the Natural Resources Conservation Service (NRCS) Hydrologic Analysis of Post-Wildfire Conditions (USDA, NRCS, 2016). Figure 3 shows the observed soil burn severity within the Spruce Wash watershed, and Figure 4 shows the distribution of the post-fire curve numbers.

Table 1. Post-fire curve number adjustments, SBS is defined as the soil burn severity assigned to the burn scar by the US Forest Service Burned Area Emergency Response (BAER) analysis.

			Curve Number		
Map Unit	Landform	Description	Pre-Fire	Low SBS	Moderate/ High SBS
0654	Hills/mountains	Mixed Conifer w/ Aspen	58	76	94
0613	Mountains/hills	Mixed Conifer w/ Aspen	58	76	94
0640	Alluvial fans	Montane / Subalpine Grassland	61	71	94
0551	Alluvial fans	Ponderosa Pine	71	71	94
0596	Mountains	Rock Outcrop	85	85	94

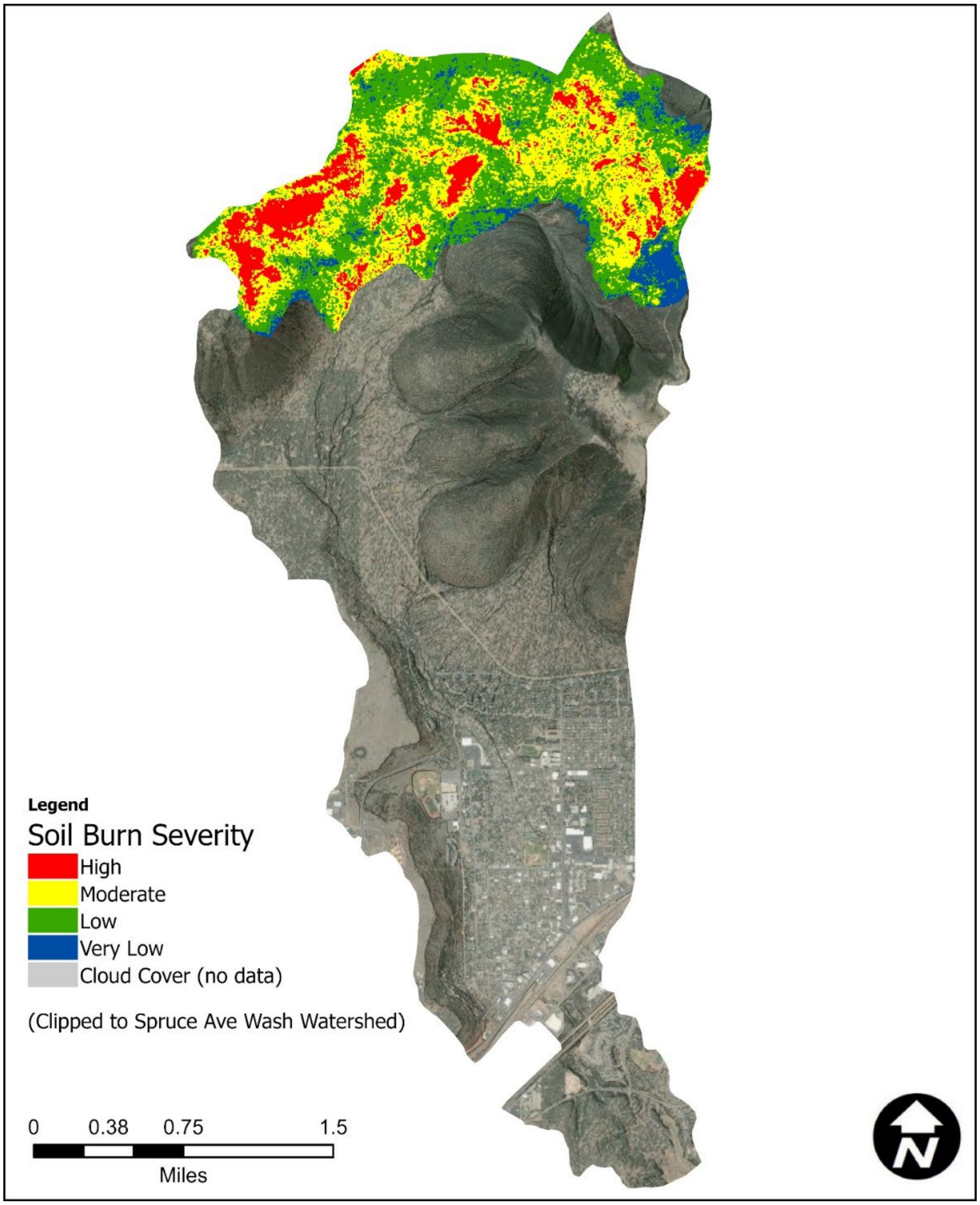


Figure 3. Museum Fire Soil Burn Severity (BAER, 2019).

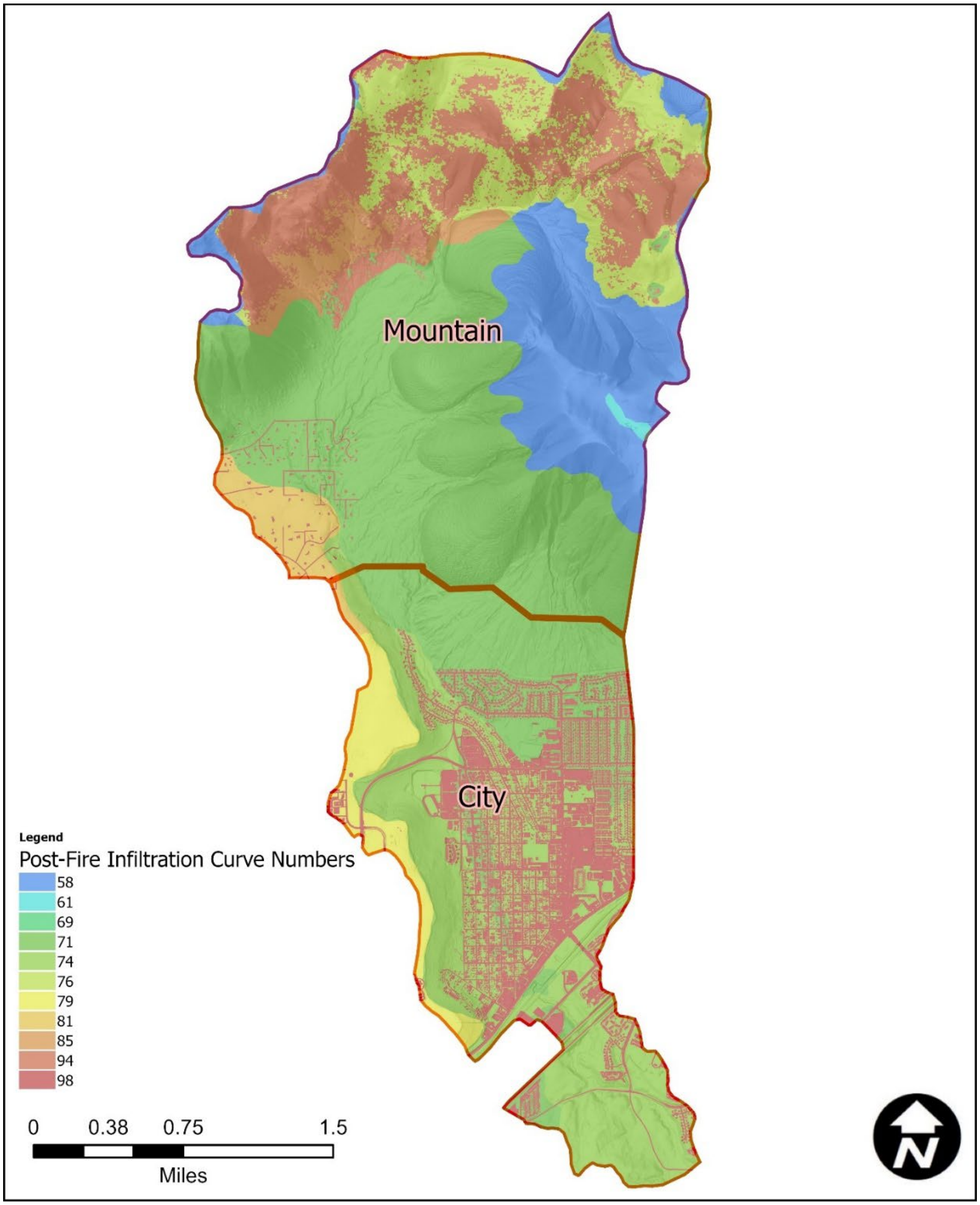


Figure 4. Post-fire curve numbers (adjusted within the burn scar in the northern portion of the watershed), Spruce Wash watershed flows from north to south.

Manning’s Roughness Coefficients

Each grid was assigned a roughness coefficient (n-value) based on its land use and condition. Manning’s n-values were adjusted per Table 2, below, to reflect realistic flow velocities and travel times. Shallow Manning’s roughness coefficients accommodate for the potential overprediction in grid velocities in areas of shallow flow. More information about the model calibration for shallow flow is available in the FLO-2D Reference Manual: Section 2.6. Figure 5 shows the spatial distribution of the different land use types within the modeling areas.

Table 2. Manning's Roughness Coefficients

Land Use	Manning’s Roughness Coefficient	Shallow Manning’s Roughness Coefficient
Mountain	0.160	0.400
Urban	0.080	0.200
Undeveloped	0.080	0.200
Impervious Areas	0.020	0.100
Main Channel Corridor	0.065	0.200
Low Burn Intensity	0.150	0.300
Moderate Burn Intensity	0.058	0.150
High Burn Intensity	0.017	0.100
Channels within Burn Scar	0.150	0.300

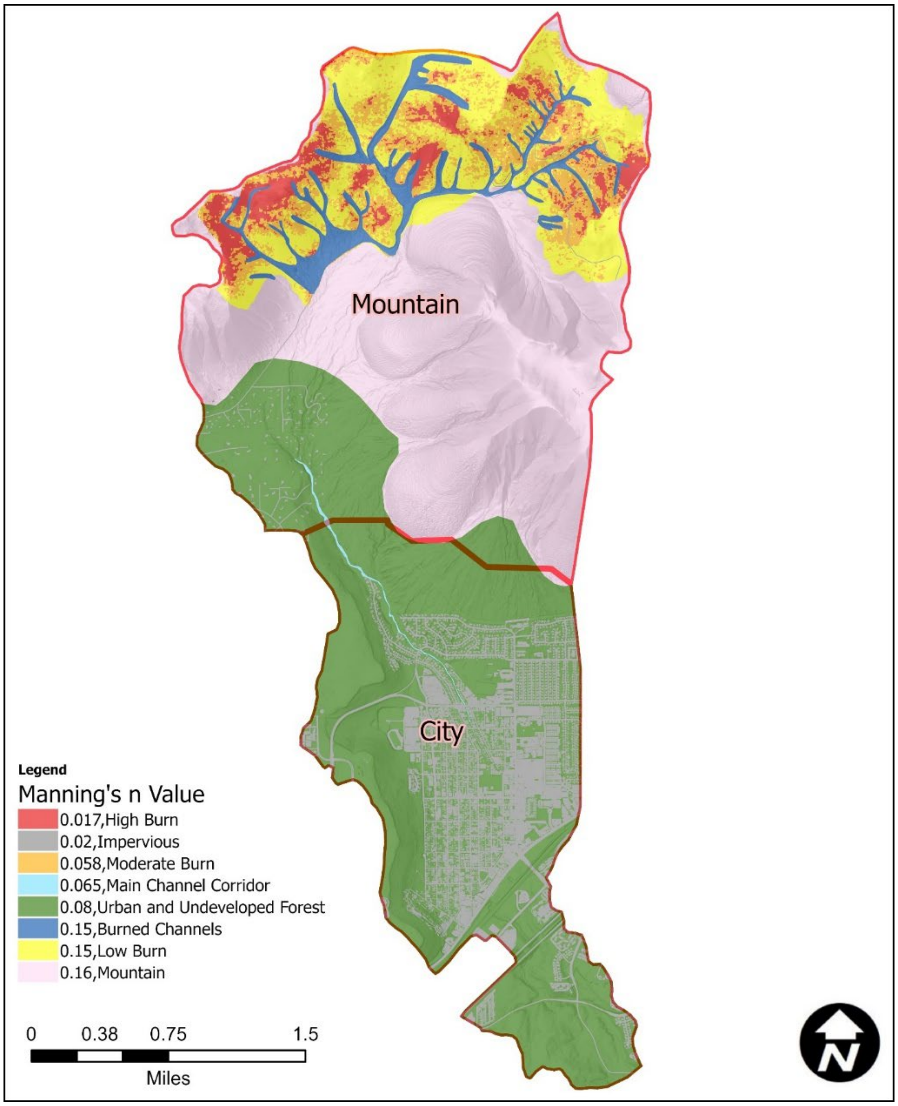


Figure 5. Manning's Roughness Coefficients

Empirical Validation Methods (Stream and Rain Gauges)

Four real time rain gauges are installed in the Museum Fire burn area to provide precipitation data to inform modeling and to provide early flood alerts to the community. These gauges are labeled Museum North, South, East, and West as determined within the burn area (Porter et al. 2021). Stage gauges also occur in the Spruce Wash watershed and include “Upper Oldham” and “Above Paradise” as camera only gauges, Museum South has a downward looking radar as well as a camera, and Above Linda Vista is a pressure transducer. Figure 5 is orientated with North on the “up” side and flow direction generally north to south (Upper Oldham as a headwater gauge and Above Linda Vista as the most downstream gauge described in this paper). Locations are included in the Flagstaff gauge report (Schenk et al. 2021) and are found online in real-time at: https://www.flagstaff.az.gov/4111/Rainfall-and-Stream-Gauge-Data. A stage-discharge relation was created at each stream gauge site using HEC-RAS and surveyed cross-sections.

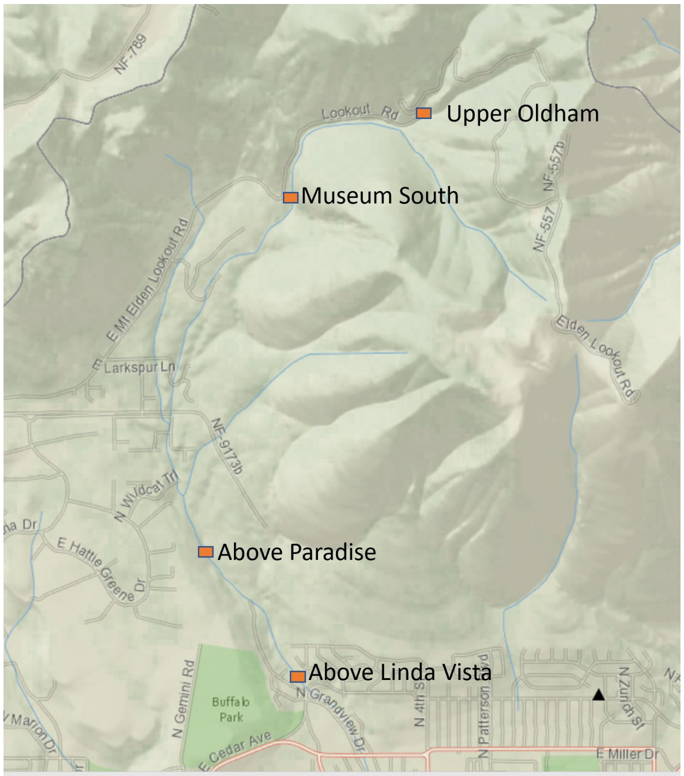


Figure 6. Map of stream gauges used in this report for model validation. Upstream is to the north (top of the figure), scale of the map is approximately 3 miles in the vertical and 2.5 miles horizontally (approximate).

Results

FLO-2D Modeling Results

FLO-2D Floodplain cross sections allow users to query flow hydrographs and peak discharges throughout the modeling domain. The modeled peak flow events for the selected cross sections are shown in Table 3 which correlate with the location shown in Figure 7. Additional floodplain cross sections were created but not shown in this paper. To illustrate the short lag time between rainfall and peak flow, Figure 8 shows the rainfall depths and runoff hydrographs for each of the mountain floodplain cross sections provided in Table 3. Discharges increases significantly from pre-to post-fire conditions. In Spruce Wash, directly upstream of the City Neighborhoods, the modeled discharges increased by approximately 10 times.

Table 3. Cross Section Peak Flow Summary

FPXSEC IDNUM	Location	Peak Discharge (cfs)			
		100-year 6-hour	1-inch	2-inch	3-inch
63m	Spruce Ave Wash near Southern Fire Boundary	1,284	258	1,127	2,459
130m	Western Tributary near Fire Boundary	751	146	638	1,317
10m	Western Tributary near North MEE	750	140	627	1,490
4m	Spruce Ave Wash near North MEE	705	166	656	1,001
98m	Spruce Ave Wash near South MEE	1,587	250	1,407	3,483

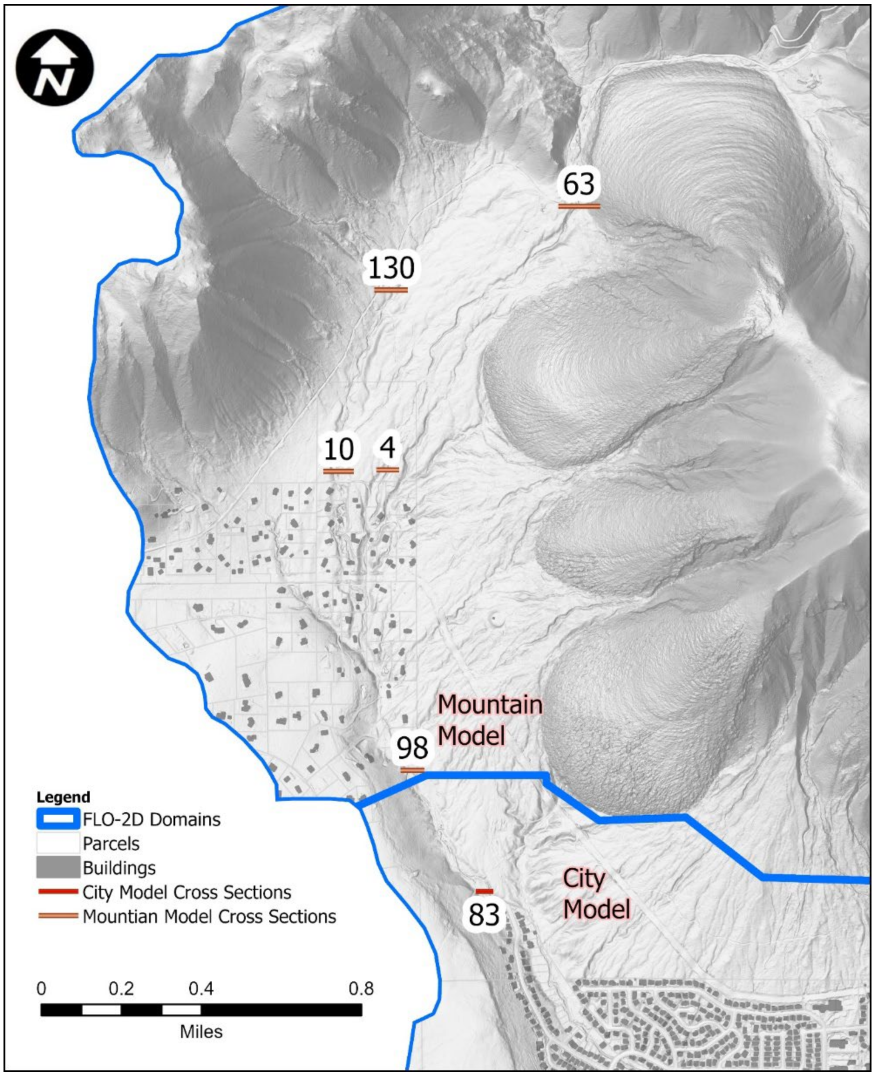


Figure 7. Summary discharge locations for the northern segment of the watershed (for reference to Table 3 results).

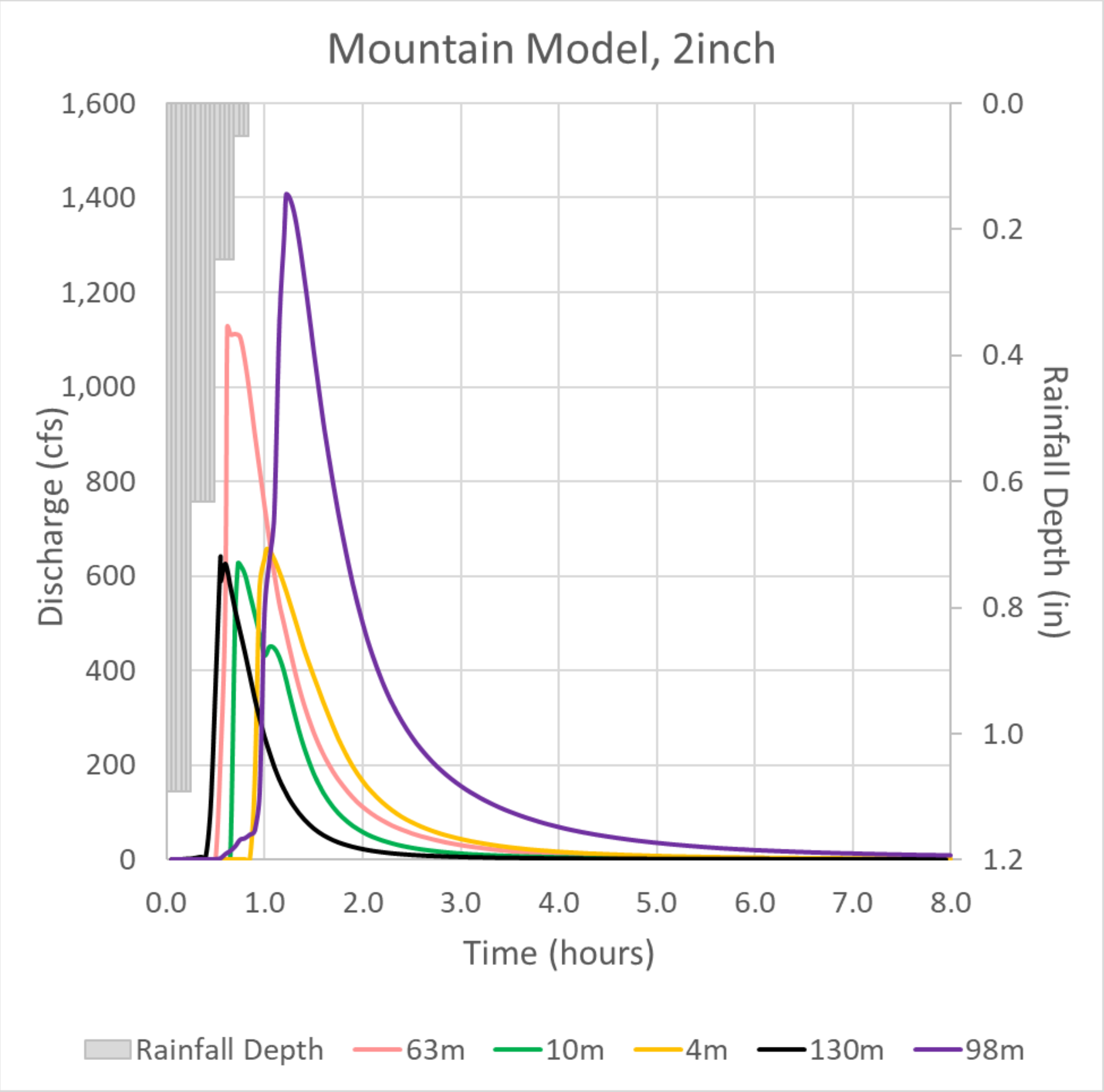
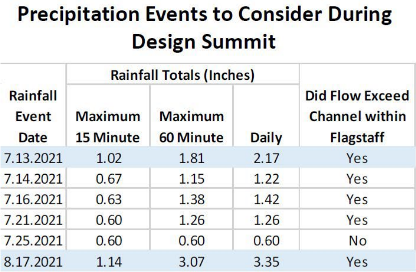


Figure 8. Rain hyetograph and floodplain hydrographs for the "Mountain" model cross sections (2 inch rain in 45 minute storm).

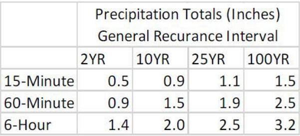
Empirical Validation Results (Stream and Rain Gauges)

Precipitation events in 2021 are provided in Figure 9 and include the recurrence interval as determined by the current edition of the NOAA Atlas 14 precipitation table for this section of Flagstaff.



Precipitation Events to Consider During Design Summit

Rainfall Event Date	Rainfall Totals (Inches) Maximum 15 Minute	Maximum 60 Minute	Daily	Did Flow Exceed Channel within Flagstaff
7.13.2021	1.02	1.81	2.17	Yes
7.14.2021	0.67	1.15	1.22	Yes
7.16.2021	0.63	1.38	1.42	Yes
7.21.2021	0.60	1.26	1.26	Yes
7.25.2021	0.60	0.60	0.60	No
8.17.2021	1.14	3.07	3.35	Yes



	Precipitation Totals (Inches) General Recurance Interval 2YR	10YR	25YR	100YR
15-Minute	0.5	0.9	1.1	1.5
60-Minute	0.9	1.5	1.9	2.5
6-Hour	1.4	2.0	2.5	3.2

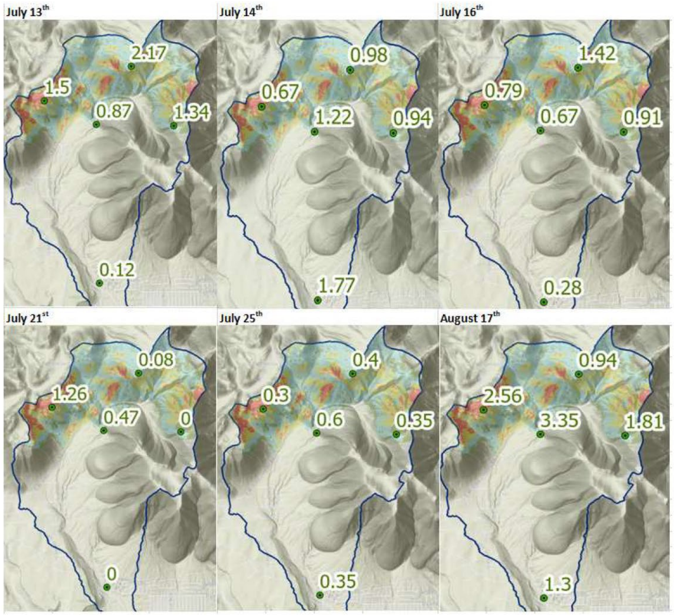
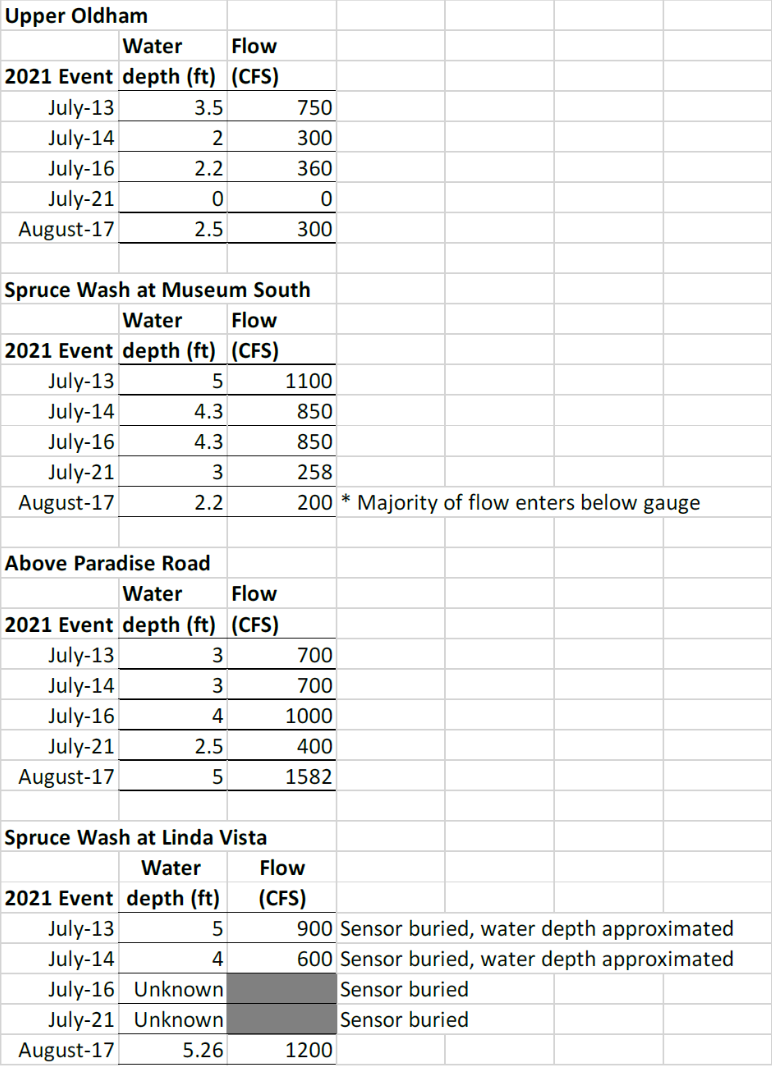


Figure 9. Precipitation patterns and events from the four Museum rain gauges (top four numbers) a downstream gauge not used for modeling (Spruce Wash at Linda Vista) and summary results. The summary NOAA Atlas 14 recurrence table is provided in the lower left.

Overbank flooding was observed on July 13th, 14th, 16th, 21st, and on August 17th. The largest event was August 17th with considerable flooding through the Paradise, Grandview and Sunnyside neighborhoods (Figure 5). Stream gauges captured some of the events however there was damage to both Museum South and Spruce Wash at Linda Vista gauges at different points in the flood cycle. The Linda Vista gauge operates on a contact pressure transducer. Data at this gauge was affected by channel sedimentation that buried the sensor providing suspect data throughout the monsoon season. Camera gauges at Upper Oldham, Museum South and Above Paradise provided precision records during each event. Flow approximations are provided in Table 4.

Table 4. Flow approximations, in cubic feet per second (CFS), at select gauges for flood events of 2021. All approximations are from stage-discharge relations that may have changed between events due to change in channel geometry during events. Channels were surveyed in 2021 before events. The Upper Oldham and Museum South gauges are located above major tributaries and do not capture all burn scar derived flows.



Upper Oldham

2021 Event	Water depth (ft)	Flow (CFS)
July-13	3.5	750
July-14	2	300
July-16	2.2	360
July-21	0	0
August-17	2.5	300

Spruce Wash at Museum South

2021 Event	Water depth (ft)	Flow (CFS)	
July-13	5	1100	
July-14	4.3	850	
July-16	4.3	850	
July-21	3	258	
August-17	2.2	200	* Majority of flow enters below gauge

Above Paradise Road

2021 Event	Water depth (ft)	Flow (CFS)
July-13	3	700
July-14	3	700
July-16	4	1000
July-21	2.5	400
August-17	5	1582

Spruce Wash at Linda Vista

2021 Event	Water depth (ft)	Flow (CFS)	
July-13	5	900	Sensor buried, water depth approximated
July-14	4	600	Sensor buried, water depth approximated
July-16	Unknown	▨	Sensor buried
July-21	Unknown	▨	Sensor buried
August-17	5.26	1200	

Discussion and Conclusions

Six storms from the 2021 monsoon season were considered during the calibration and verification of the flood model results. The top table in Figure 9 shows the maximum rainfall for the 15-minute, 1-hour, and daily totals for each storm event. Figure 9 shows the rainfall measured on each day at each of the Museum Fire rain gauge stations and Table 4 provides approximate flow results. These observed events do not replicate the storms modeled, but they do provide guidance to help select parameters used within the models for planning purposes. It should be noted that the model results assume a normal soil saturation, which is more representative of an initial storm rather than a later storm which usually has more saturated soils due to subsequent rain events. Spatial-temporal rainfall variability and antecedent soil moisture was not modeled and likely could impact the flood risk mapping, the state of that science is still being developed for small (< 50 sq. mile) watersheds (e.g. Zhu et al. 2018).

Streamflow gages within the watershed did not always measure the flow depth accurately due to the sediment and debris in the runoff and due to changing channel conditions, so detailed calibration is not available (Figure 10). Monitoring cameras and observations indicated that during the largest events during the monsoons, flow rates approaching the City of Flagstaff were in the 1,000 to 1,500 cubic feet per second range. The largest storm (8/17/21) averaged just over 2 inches in 1-hour over the watershed. The second largest storm (7/13/21) averaged 1.5 inches in 1-hour over the watershed. The 2" model approximates 1,402 cfs at the City Limits. Based on this data, the team felt that the models adequately represented flood risk.

Figure 10. Channel configuration at Museum South in June 2021 and August 2021, note the change in channel geometry. Channel geometry changed drastically after each storm, some with net scour and others with net aggradation, making stage-discharge determinations challenging.

The model results provide a Fall 2021 snapshot in time of the hydrologic and hydraulic conditions of the Spruce Wash watershed which was impacted by the 2019 Museum Fire. Key assumptions in the modeling are:

- This model assumes a uniform rainfall throughout the watershed. Realtime events vary in rainfall distribution, but the modeled rainfall provides an analysis that can be used to evaluate flooding potential for a given storm precipitation total.
- This model assumes a 'normal' soil saturation level. During a monsoon season, soils may or may not be more saturated. If it is more saturated, then the watershed could be more responsive and could result in higher flows.
- The watershed will continue to change and evolve during flood events and those changes are not reflected in this study. A fall 2022 soil survey indicated a flow reduction of approximately 20% based on improving soil and vegetation conditions, this year three post-fire improvement is not presented in this paper as the results are preliminary.
- The modeling does not include bulking due to sediment concentrations or mudflow considerations. Many studies indicate that a bulking factor in exceedance of 25% is warranted, however without detailed empirical event based sediment monitoring this has been excluded (Brunkal and Santi 2017; Schenk et al. 2023). On-forest alluvial fan improvement projects, which reduce downstream debris impacts, were completed in 2022 after the completion of this project data collection and the benefits were not seen, or modeled, in this paper.
- There are channel geometry changes that occurred during flood events within and below the burn scar from scour and aggradation. This produced some noticeable changes in velocities and depths in the incised channels in and around the burn scar, changes in the timing of peak flow rates, and slight changes to flow patterns above Mount Elden Estates due to sediment and debris aggradation. These changes produce a change in peak flow and peak flow timing that is within 10% of the original 2019 channel conditions (full results are not presented in this paper).

The City and Coconino County Flood Control District have used these modeling (and empirical validations) to understand the short-term flood risk and to plan for the long-term watershed conditions. Flagstaff City Council approved an administrative floodplain spatial overlay of the 2” rain event model to help guide future development within the flood impact area (Figure 11). This administrative floodplain overlay has the same development overview and restrictions as a typical FEMA Special Flood Hazard Area Zone AE Floodplain (commonly called FEMA floodplain AE). This administrative floodplain designation is intended to be revised through time until the watershed has stabilized and a new FEMA floodplain can be mapped through a typical Letter of Map Revision (LOMR) process.

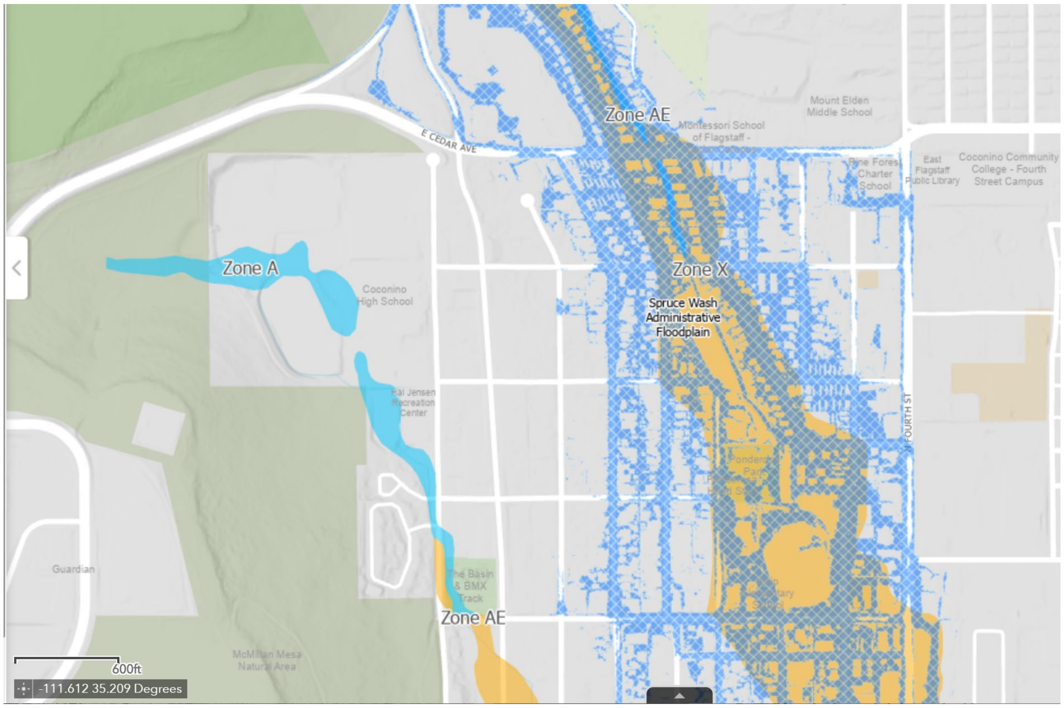


Figure 11. The Spruce Wash administrative floodplain designation (in blue hatch) with FEMA floodplains marked in blue (Zone A and Zone AE) and 500 year floodplains marked in orange (shaded Zone X).

Stormwater capital improvements, including (from headwater to downstream) alluvial fan restorations, regional detention basins (Killip, Park Way), channel capacity improvements (Paradise and Dortha stream reaches), and flood levees (Grandview Avenue) are also driven by this modeling effort. Short term response efforts have also been crafted around this modeling and the real-time rain and flow gauges (see Schenk et al. 2021 for network details). These response efforts include an integrated early alert and emergency response network between the City and the County based on rain and flow thresholds and known channel, or storm drain, bottlenecks.

It is the hope of the authors that this case study, and the concurrent sediment modeling paper, will help increase the body of knowledge on applied post-wildfire flood and stormwater management at the local government scale and show the need for Federal and State funding for these types of studies and master plans. Dedicated funding for post-wildfire modeling for local governments is imperative for life and safety emergency management as well as for watershed restoration and stormwater management.

Acknowledgements

This project, and the concurrent sediment project, are a collaboration of many partners from the Coconino County, City of Flagstaff, Forest Service, National Weather Service, Northern Arizona University, and a great deal of local hydrology and civil engineering consultants. Listing everyone who made this possible would take several pages and likely still miss a handful of valuable contributors. Special acknowledgement goes to Lucinda Andreani, Coconino County Flood Control District Administrator, for her leadership during the multiple fires and subsequent flood events. Funding was provided by Coconino County general fund, Coconino County Flood Control District, and the City of Flagstaff Stormwater Fund. External peer review was provided by Guo Yu of the Desert Research Institute.

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