EVALUATING EROSION RISK MITIGATION DUE TO FOREST RESTORATION TREATMENTS USING ALLUVIAL CHRONOLOGY AND HYDRAULIC MODELING

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ABSTRACT

Previous and recent studies indicate that severe forest fires in the arid Southwest make watersheds highly susceptible to post-fire flooding, sediment mobilization, and debris flows. Forest fires have increased in size and severity as a result of land use practices, including fire suppression throughout the twentieth century and climate change that has increased the occurrence of drought. Forest restoration is being planned and implemented in many locations to reduce the risk of severe forest fire and subsequent flooding that can have negative impacts on communities at the Wildland-Urban Interface and communities downstream of forested watersheds. The Flagstaff Watershed Protection Project (FWPP) is a forest thinning project to treat watershed that would result in dangerous flooding if they were to burn in a wildfire. Schultz Creek is a major tributary of the Rio de Flag watershed of the City of Flagstaff, Arizona, which is being treated by the FWPP. This study used alluvial chronology to study the recent geologic history of Schultz Creek and hydraulic modeling to predict how peak flood flow magnitudes and stored sediment could be affected by severe wildfires and FWPP treatments in and adjacent to Flagstaff, Arizona. The alluvial chronology utilized C^{14} dating of charcoal fragments for age constraints. Sediments have been accumulating in the channel for ~7,000 years without any major disturbance such as a severe fire on the watershed scale or high magnitude flooding. Analyses indicate that over 1.5 million tons of sediment may be stored in the main channel. Hydraulic modeling using HEC-RAS 4.1 indicates that forest treatments reduce the magnitude of post-fire flow at the confluence of the watershed by up to 55%. The results of this study are relevant to the City of Flagstaff citizens whose votes approved use of municipal bond funds to conduct forest restoration,

and to communities across the Southwest that could benefit from forest restoration in their watersheds.

Acknowledgements

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INTRODUCTION

Wildfires have been increasing in frequency and severity in the southwestern United States within the last few decades resulting from land management practices during the last century. Prior to European settlement, which began in the late 19th century, the ponderosa pine forests of the American Southwest were fire-adapted and experienced low-to-moderate severity surface fires with an occurrence frequency averaging every 2-12 years (Covington and Moore, 1994). These naturally burning fires eliminated excess woody fuels and brush, keeping the forests open and resilient to severe wildfire. The structure of Southwestern forests has been altered by logging, fire suppression, cattle grazing, and road building (Covington, 2003). The resulting increased density of younger trees and accumulation of duff and litter are fuel for wildfires, thus the risk of high-severity wildfire has increased (Covington and Moore, 1994). Pre-European settlement ponderosa pine forests had regular, low-intensity fire regimes, which have gradually been replaced by dangerous and severe crown fires (Harrington and Sackett, 1990). Recent notable catastrophic wildfires include the Wallow (2011; 538,000 acres), Rodeo-Chediski (2002; 468,000 acres), and Dude (1990, 28,000) fires, all of which occurred in Arizona. Studies show that Arizona and New Mexico have lost up to 18% of high-altitude forests over the past 24 years due to drought, pest infestation, and wildfire, and that Arizona could lose over half of its high-altitude forests by mid-century (Koestner et al., 2011a).

Increased risk of forest fires is only one of many negative consequences of an overly-dense forest. There can also be impacts to public safety, ecosystem health, and water quality and supply. The dense canopy and lack of canopy openings of modern forests reduce water yield by limiting the pathways for precipitation to reach the forest floor, reducing infiltration (Covington and Moore, 1994; Bosch and Hewlett, 1982). Reduced infiltration decreases streamflow and the amount of water in storage. Dense canopy cover also increases evapotranspiration and decreases snowpack accumulation (Stegman, 1996), which is the main source of total groundwater recharge in northern Arizona. The unnaturally dense forests not only limit the amount of water available for human consumption but threaten the healthy function of forested watersheds and their dependent ecosystems (Neary et al., 2003). The increased risk of catastrophic wildfire poses direct threats to communities in the Wildland Urban Interface (WUI), as well as water users downstream of burned watersheds. Property damage can be caused directly by fire or indirectly by flooding and sediment mobilization during monsoonal precipitation or snowmelt events following severe burns.

1.1 - BACKGROUND

1.1.1 - Climate, Vegetation, and Geology

The climate in Northern Arizona is bimodal, characterized by droughts in the fall and spring, and precipitation in the summer and winter. Summer storms are commonly intense, local, and of short duration, generally occurring from early July through September (Baker, 1999). This is referred to as the monsoon season. Winter precipitation accounts for 60% of the annual precipitation, and snowmelt supplies almost 97% of the annual water yield (Baker, 1986). The average annual precipitation for the Upper Rio de Flag drainage basin ranges between 56.4 cm at the Fort Valley

Experimental Forest weather station (2,240 m) to about 89 cm on the San Francisco Peaks at 3,650 m (Leao, 2005). Ponderosa pine and mixed conifer type forests in this region are most prone to fire during the hot, dry period in early summer months.

The study area for this thesis is located in the San Francisco Mountains, an area geologically dominated by silicic lava domes, and two stratovolcano cones of interlayered lava flows and pyroclastic deposits ranging in composition from andesite to rhyolite (Holm, 1988). Geology of the Schulz Creek watershed is Pleistocene-aged dacite breccia and dacite lava domes with limited exposure of older basalt flows. Prior to this study surficial deposits along Schultz Creek were mapped cumulatively as undifferentiated alluvium, talus, till, and colluvium.

1.1.2 - Post-fire Slope Processes

Catastrophic wildfires drastically change watershed response to precipitation, mainly by increasing overland flow (Figure 1, Figure 2). In Northern Arizona, the juxtaposition of severe wildfire and intense precipitation of the monsoon results in a high potential for flooding, erosion, and debris flows, particularly on steep slopes (DeBano et al., 1998; Neary et al., 2003). The burning of organic matter and forest floor litter reduces infiltration. Storage capacity of surface materials is reduced due to fire's alteration of clay minerals and organic matter; soil macropore volume at the surface is reduced by severe wildfire (Neary et al., 2003). Soils can become hydrophobic from the heat of high severity fires increasing runoff rates. Exposure of bare mineral soils increases from high-severity fire. These soils are sensitive to rain-drop splash impact which can seal soil pores and further reduce infiltration and increase overland flow (Neary et al., 2003). Overall infiltration rates have been observed to be reduced by

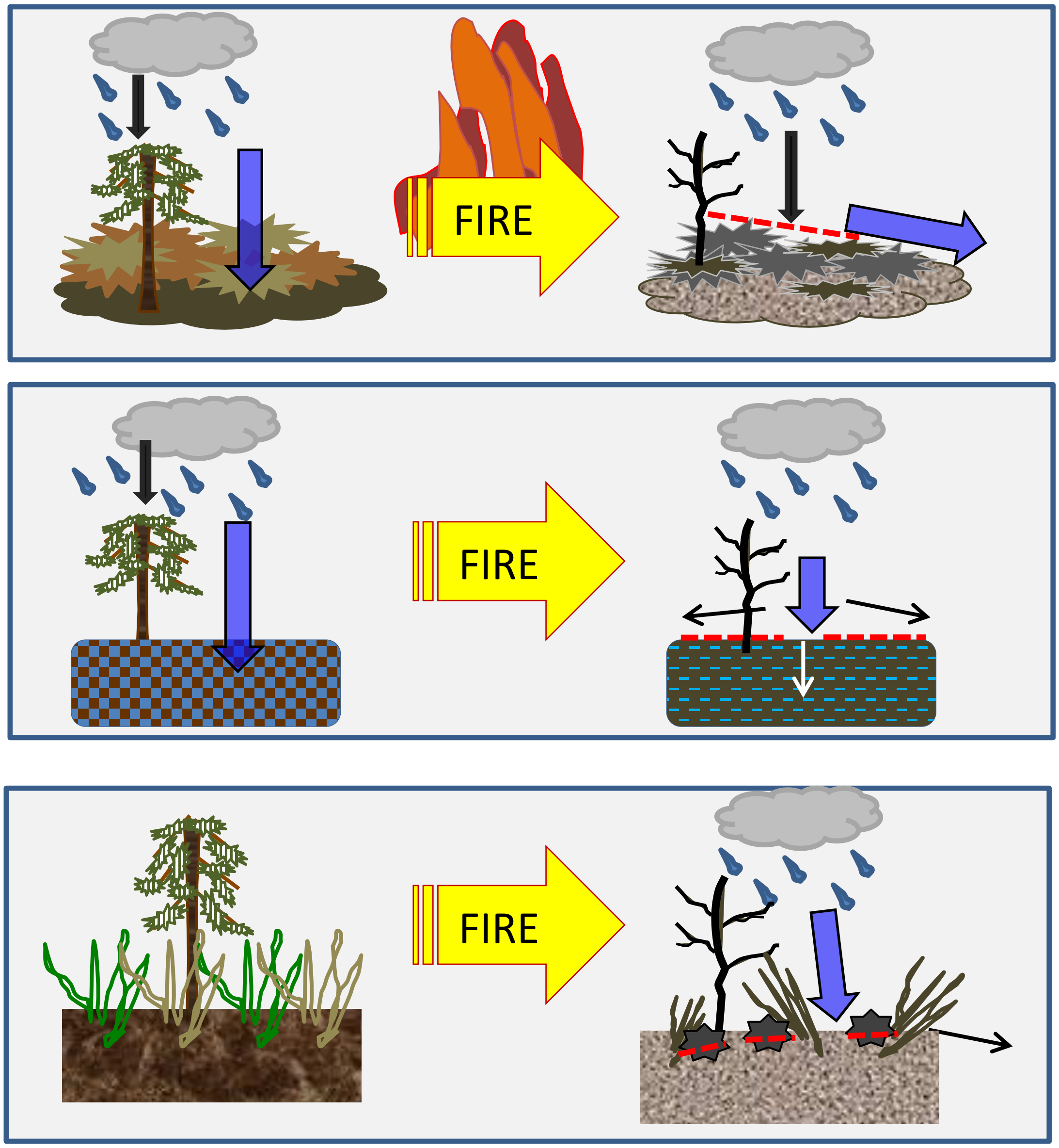


Figure 1. Conceptual diagrams of the effects of wildfire on forested watersheds. Fire decreases infiltration and evapotranspiration which cause increases in runoff. Loss of tree canopy results in decrease in evapotranspiration allowing significantly more precipitation to reach the ground surface. **A.** Forest floor organics and litter become hydrophic. **B.** Soil-water storage is reduced due to fire altering soil structure; macropore volume is significantly reduced. **C.** Fire eliminates fine roots that bind soils together and cover mineral soils. After a fire, bare mineral soils become exposed and are susceptible to rain-drop splash pore sealing.

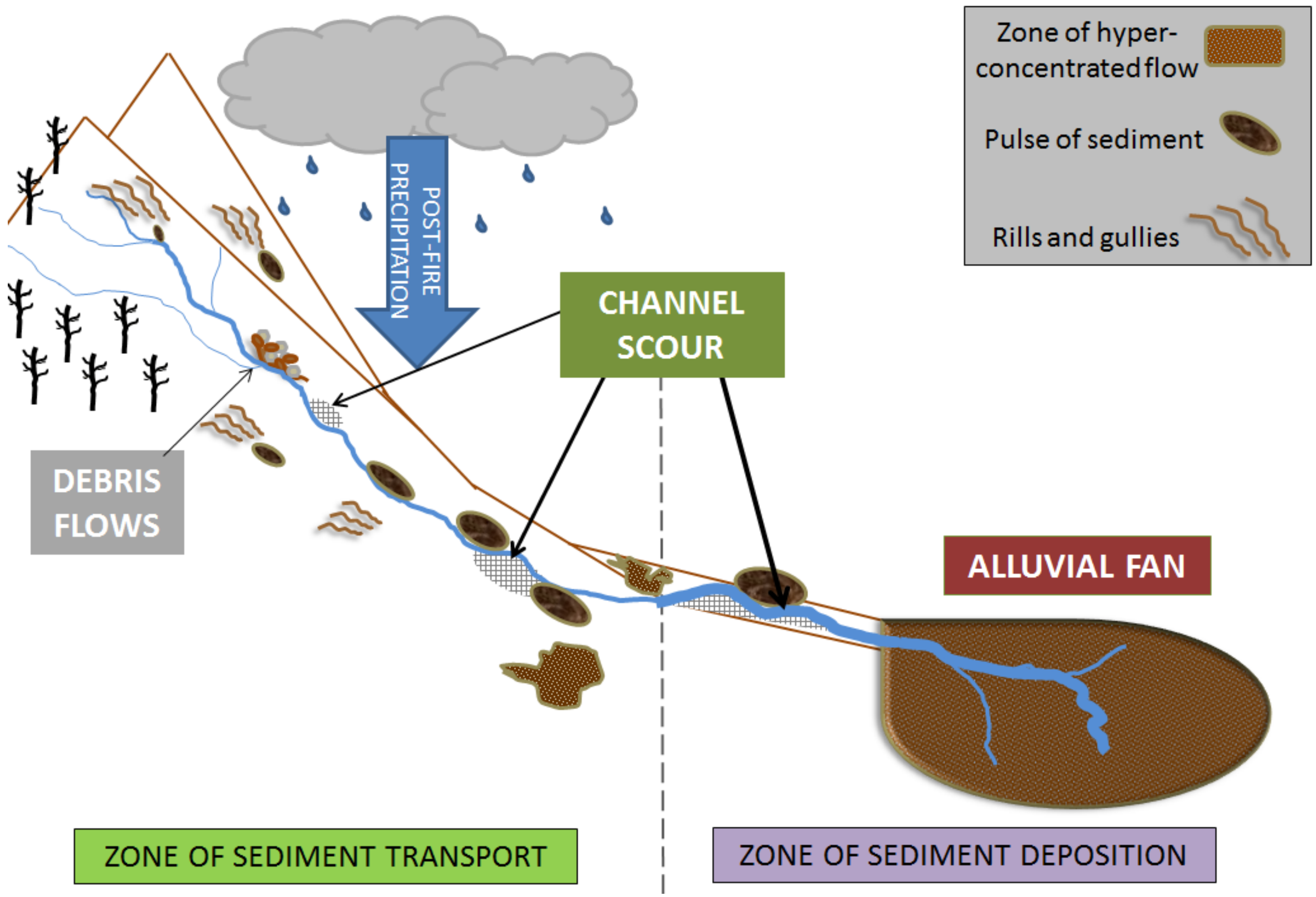


Figure 2 – Conceptual diagram of major post-fire slope processes as a result of precipitation. Debris flows are generally confined to upper slopes. Sediment pulses can contain hyperconcentrated flow. Impacts of post-fire runoff and erosion extend beyond the alluvial fan and can alter processes throughout the entire watershed. For example, sediment can damage municipal utilities and flood routing structures.

several orders of magnitude on burned landscapes (Ice et al., 2004). Surface materials that are typically binding such as organics lose their binding ability when burned at high temperatures and result in increased dry ravel from hillslopes. Burning of vegetation decreases the stability of slope material by destroying fine root structures that hold soil and soil aggregates together, increasing potential for sediment mobilization (Moody et al., 2013). The effect of decreased root stability is more pronounced several years after fire (8-12, Moody et al., 2013) when the roots of dead trees and shrubs eventually decay.

Reduced vegetation and decreased infiltration rates resulting from fire lead to high runoff rates and dramatically increased peak flows, commonly from 500 to 9,600% of pre-fire peak flows in the southwestern U.S. (Neary et al., 2003; Robichaud et al., 2000; Scott, 2006). Higher and flashier peak flows can increase bedload and suspended sediment transport capacities. Combined with post-fire increases in sediment availability from bare soil exposure and by elimination of stabilizing root structures, erodibility of burned landscapes is very high (Moody et al., 2013; Scott, 2006). For example, after the 1994 Rabbit Creek burn in Idaho, moderate 5-year storms resulted in a 1,000-year flood event with an estimated 383,320 m^3 of sediment transported in the watershed's streams, while there was little to no sediment response from unburned areas (Ice, et al., 2004).

1.1.2 - Post-fire Sediment Mobilization

Sediment mobilization on burned watersheds is very complex and often unpredictable due to (1) spatial variability of burn severities, (2) spatial and temporal variability of rainfall, and (3) spatial variability of stored sediment within a watershed. Erosional processes have been observed and measured in an attempt to determine the primary drivers of erosion.

Sediment availability is a major control on the degree of erosion and sediment transport. The volume of stored sediment on hillslopes and in channels is incredibly variable between watersheds and is dependent on how long sediments have been accumulating without major disturbance (such as wildfire). Studies of post-fire sediment yields in the western U.S. have revealed that about 75% of coarse-grained sediment yield comes from channels, and only 25% comes from hillslopes (Moody and Martin, 2009). On hillslopes, the volume of sediment available is mostly a function of how rapidly soil is produced from the bedrock. Available sediment in channels depends on how much time has passed since the last major erosional event and the rate at which hillslope sediment is transported to the channels. Channel sediments are stored in many different features, such as in alluvial fans, flood plains, and the bed of the active channel. The residence time of stored sediment in and around the channel can range from days to thousands of years (Swanson, 1981). Sediment accumulation rates are affected by numerous factors, both internal and external to the watershed, but in the Southwest, wildfires are the primary agent for 80% of long-term erosion (Ice et al., 2004).

Sediment is transported from hillslopes by a variety of processes including dry ravel, wind, and mass wasting. Post-fire transport of hillslope sediments is dominated by rainfall-generated runoff via rills and gullies which readily form on hillslopes during post-fire precipitation (Neary et al., 2012). Once erosion is initiated on hillslopes, the watershed response to precipitation grows increasingly more dramatic. Rills and gullies more efficiently transport runoff and sediment to channels. Channel erosion increases as discharge becomes ‘flashier’ and runoff becomes concentrated in the channels. Additionally, the more hillslope sediment contained in overland flow, the greater erosive power the runoff has. Channels can erode down to bedrock, creating slick and impermeable channel beds which rapidly transport runoff and eroded sediment downstream.

Terrain also plays a role in the degree of post-fire erosion. Burned watersheds on steep, mountainous slopes are incredibly susceptible to mass wasting during precipitation. Steep slopes decrease the shear stress necessary to initiate motion of sediment, while simultaneously increasing the boundary shear stress of flowing water (Moody and Martin, 2009; Swanson, 1981). Therefore, sediment transport potential is particularly high on steep slopes compared to other terrains.

Post-fire erosion and sediment yield has been observed to be the highest during the first year following wildfire (Swanson, 1981). In the Entiat Forest in Washington, annual sediment yields increased 7 to 20 times in the first year following a severe burn in 1970 (Ice et al., 2004). According to studies across the western U.S., abnormally high sediment yields can persist for 4 to 7 years after wildfire (Moody and Martin, 2009). Sediment yields will diminish as vegetation recovers in a burned watershed.

These fluxes in sediment can have negative impacts on water quality, which can subsequently impact riparian fauna (Rieman and Clayton, 1997). Elevated nitrogen, phosphorous, and base concentrations of calcium, magnesium, and potassium have been observed after wildfire (Ice et al., 2004). Increased stream temperatures, large sediment pulses, and debris flows can cause direct mortality of fish and other organisms. One to three years post-fire when nutrient-rich soils are present, elevated concentrations of dissolved nitrate, cations, and alkalinity have been found, and although these changes typically don’t affect aquatic biota, they can result in downstream eutrophication in lakes and reservoirs. This is not typical in Arizona due to nutrient poor soils. Indirect effects such as increased erosion, sediment transport, and turbidity are the primary causes of macroinvertebrate mortality, sometimes up to 90% (Minshall, 2003; Gresswell, 1999). Following the 1990 Dude Fire in the Tonto National Forest in Arizona, post-fire runoff essentially extirpated salmonids in creeks in the burn area (Rinne, 1996). This was likely due to ash flows into creeks during immediate post-fire runoff. Subsequent flood flows are believed to have resulted in the extirpation of the remaining population either directly or indirectly by downstream displacement. Ash deposition in stream substrates is also fatal to aquatic macroinvertebrates by reducing oxygen levels. Macroinvertebrate communities usually recover close to prefire conditions within 10 years, although community compositions can shift (Minshall, 2003; Gresswell, 1999).

There are many risks to humans from post-fire water quality degradation. Ash that is transported downstream can contaminate drinking water. The 2012 Sunflower Fire on the Tonto National Forest resulted in ash-laden water to be transported 45 miles away to a Phoenix water treatment plant, requiring increased treatment to improve water quality to drinking standards (http://www.eastvalleytribune.com/local/tempe/article_e60b54de-ecd3-11e1-b788-0019bb2963f4.html, 2012). Increased sediment flux to reservoirs can completely compromise drinking water due to high costs of dredging and treating the water to be potable.

1.1.3 - Schultz Fire

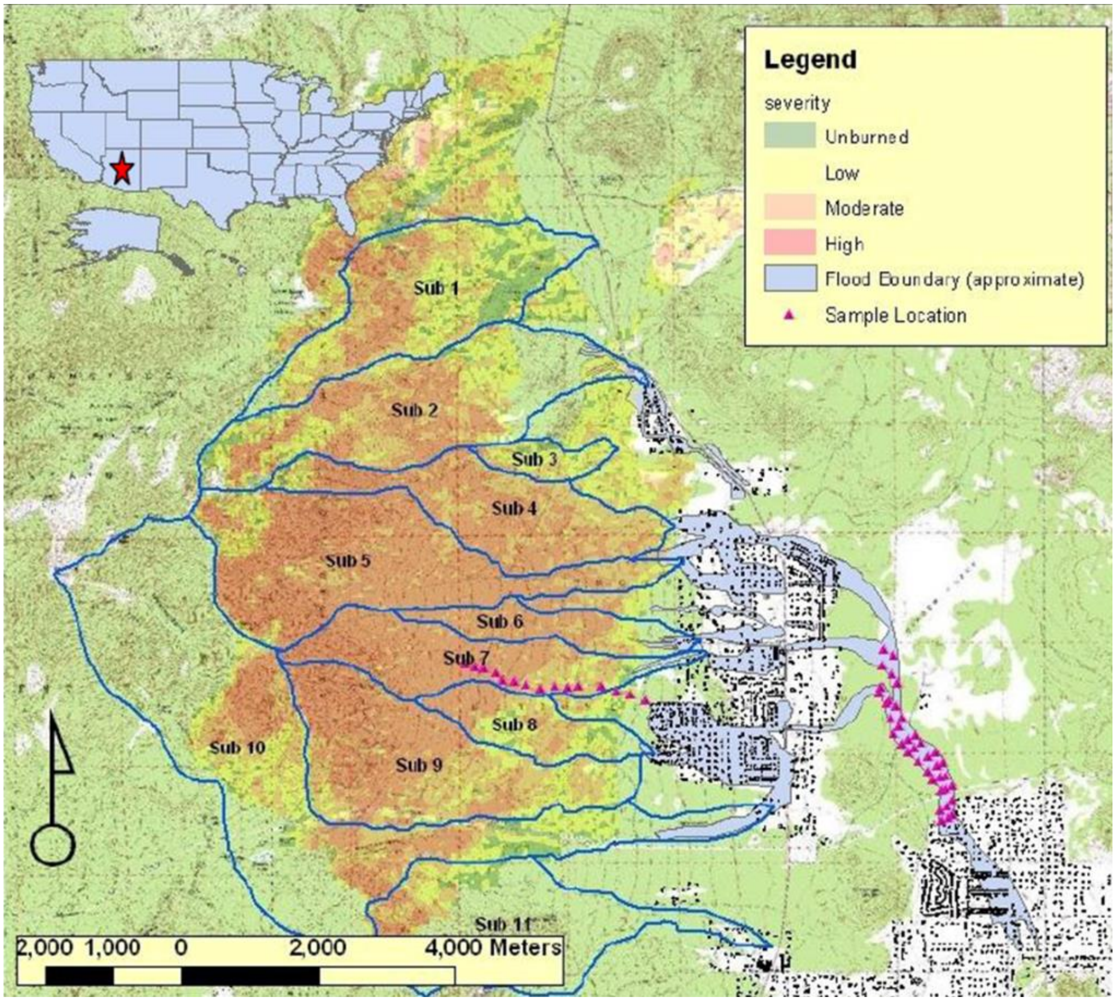


Figure 3 - Schultz Fire Burned Area Emergency Response (BAER) burn severity map. Depicts burn severity, watershed delineation, post-fire flood flow boundaries, and sediment sample locations from a grain size study. BAER basins 4, 5, 7, 8, 9, and 10 were identified as Basins of Concern. Data from Coconino National Forest. Urban areas at base of burned drainages is the Timberline neighborhood (Koestner et al., 2011b).

1.1.3.1 - Physical Impacts

In June 2010, the Schultz fire burned 15,051 acres of Coconino National Forest near the City of Flagstaff, making it the largest wildfire in Arizona in 2010. The burn was followed by the 4th wettest monsoon season on record in Flagstaff, resulting in debris flows, severe erosion, and substantial flooding in residential areas, and causing damage to property and the death of a 12-year-old girl (Koestner et al., 2011a). During the fire, over a thousand residents were evacuated and, although several watersheds burned almost completely (Figure 3), no structures were directly impacted by the fire; all property damage was caused by post-fire precipitation and associated flooding. Debris flows were confined to the upper slopes of the drainages and did not impact residential neighborhoods, but sediment and ash-laden flood flows caused extensive damage to homes and property up to 4 miles away from the burn area (Figure 4a) (Koestner et al., 2011a). Drainages in the burn area descend from steep mountain slopes into confined channels within alluvial fan deposits within the forest boundary. Channels emerge from the forest onto unincised, younger alluvial fans which have been heavily modified by housing developments (Figure 3). The steep slopes and rapid slope transitions in the burn area magnify erosional effects. Confined reaches, such as those that are typical of the high gradient mountain slopes of the Schultz burn area, act as transport zones for sediment. Sediment gets deposited in the zones of slope transition, such as the piedmont zone in the Schultz burn area (Koestner et al., 2011a).

There were several high-magnitude precipitation events following the Schultz Fire, but the most damage occurred during the July 20, 2010 storm which had a 10 year average return interval (Carroll, 2011). The burned area received up to 75 mm of rain,

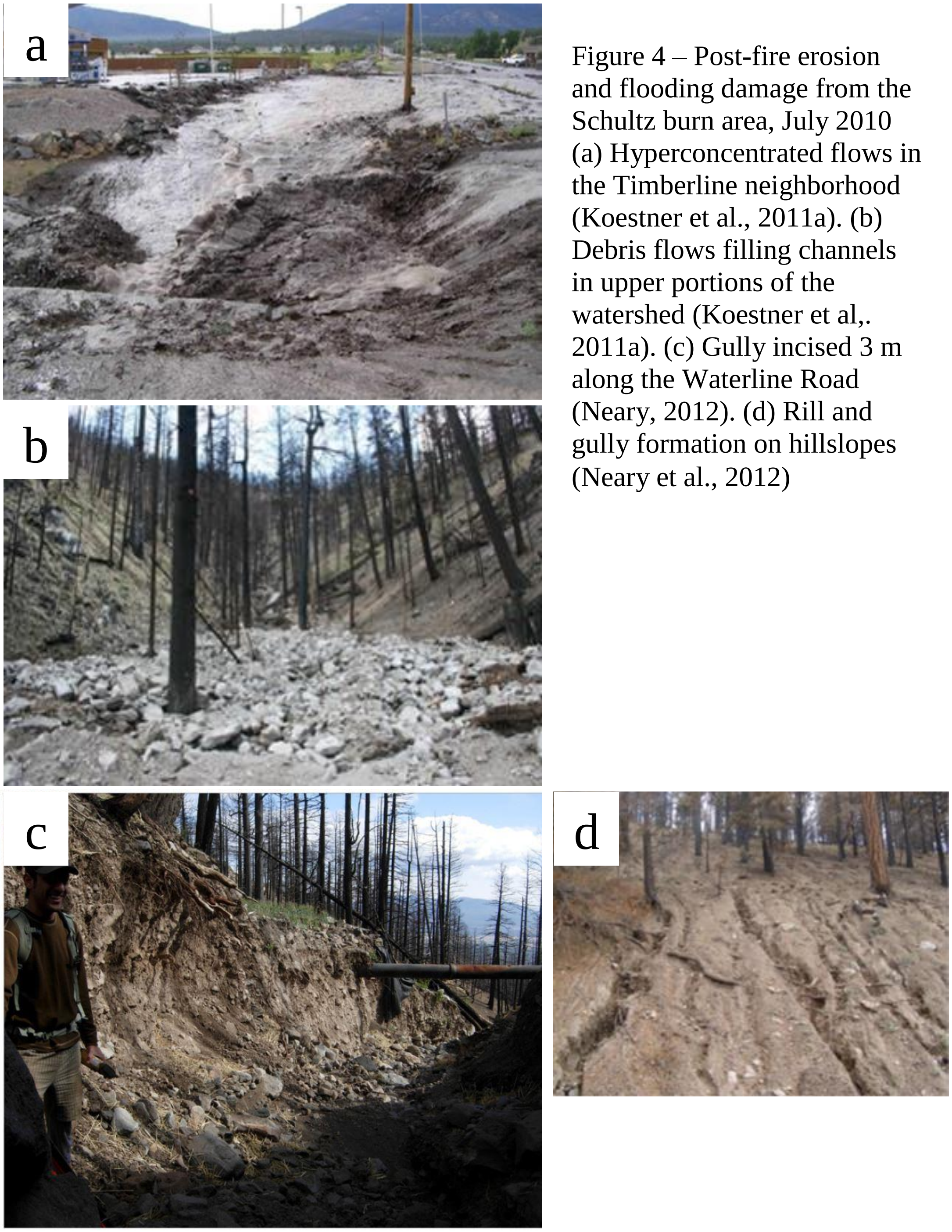


Figure 4 – Post-fire erosion and flooding damage from the Schultz burn area, July 2010 (a) Hyperconcentrated flows in the Timberline neighborhood (Koestner et al., 2011a). (b) Debris flows filling channels in upper portions of the watershed (Koestner et al,. 2011a). (c) Gully incised 3 m along the Waterline Road (Neary, 2012). (d) Rill and gully formation on hillslopes (Neary et al., 2012)

with 45 mm (1.78 inches) falling within a 45 minute period. About 25 mm (an inch) fell during a 10-minute peak intensity period, ~33% of the total precipitation during this event (Koestner et al. 2011a). Debris flows on upper slopes of most watersheds scoured up to 4 meters depth, exposing bedrock in the high gradient channels (Figure 4b). Rills and gully formation on steep slopes contributed to the channel scouring down to bedrock (Figure 4c, d). The combination of these effects resulted in flashy discharge and dangerous flood flows moving downslope.

Several Burned Area Emergency Response (BAER) treatments that focused on erosion control failed during the high intensity precipitation event on July 20, 2010. Flagstaff's waterline road was armored to protect a water pipeline that transports a portion of the city's drinking water. Instead of preventing erosion, the rock armoring contributed to erosional damage because the rocks were not large enough to remain stable in the high velocity flood-flows coming off the steep slopes (Neary et al., 2011). As a result, the pipeline was damaged in 28 locations
(Koestner et al., 2011a). The failure of this and other BAER treatments can be attributed to severe post-fire conditions and steep slopes. It is possible that more appropriate treatments could have been selected with an improved understanding of this watershed's particular responses to post-fire flooding; there were no detailed data available on channel morphology and conditions before the fire (Carroll, 2011). Moody and Martin (2009) surmise that soil availability is the primary factor that determines post-fire sediment yields. Improved surficial mapping and characterization of the watershed's geomorphology and potential sediment sources would have significantly aided design and

application of BAER treatments, as well as long-term post-fire erosion mitigation treatments (Carroll, 2011).

1.1.3.2 - Cost of Wildfire

In 2010, immediate response alone cost $13.6 million for the fire and $12.3 million for the flood. Mitigation in 2011 and 2012 cost an additional $13.7 million, with $19 million more expected in the years to follow, resulting in a total cost of $58.6 million solely for suppression and mitigation (Burke, 2012). The total impact of the Schultz Fire is estimated to be between $133 million and $147 million when considering factors such as damages to personal property, destruction of habitat, cleanup costs, Flood Insurance Premiums, and more (Combrink et al., 2013). Even this estimate is considered conservative due to exclusion of expenses associated with volunteer work, destruction of archaeological sites, physical and mental health problems, and other long-term impacts. If a fire and flood of this same magnitude hit downtown Flagstaff and damaged businesses and historic infrastructure, the costs would be greater. A study (Arizona Rural Policy Institute, 2014) indicated that Flagstaff Watershed Protection Project restoration (section 1.2.4) on the Dry Lake Hills in the Rio de Flag watershed could mitigate $489 to $986 million of damages that could result from fire and post-fire flooding. This estimate includes cost damages to government and utilities, infrastructure and property, property value, retail sales, habitat, communication towers, and railroad interruption.

There have been other studies done to predict the costs of flooding damages along the Rio de Flag prior to the flooding following the Schultz Fire. The U.S. Army Corps of Engineers (2000) predicted that a flood large enough to impact the 500-year floodplain in the Rio de Flag watershed could damage 1,500 structures, would directly affect over half of Flagstaff's population, and would cause approximately $93 million of economic damage. After the 2002 Rodeo-Chediski fire that burned 462,614 acres, one of the largest fires in Arizona history, the Flagstaff Fire Department (2003) estimated how a fire of the same scale and severity would impact Flagstaff financially. Based on conservative estimates of length, severity, and location of a similar burn in Flagstaff, the impacts to sales and revenue from tourism, property tax, and business revenue were evaluated for a single year following the theoretical burn. The study estimated costs of over $69 million. This amount is likely an underestimate due to the omission of post-fire flooding damage costs and recovery costs.

1.2 - FOREST RESTORATION

1.2.1 - 4FRI

Methods of forest restoration that decrease the risk of forest fire and improve water yield in semi-arid, conifer-dominated watersheds have been developed (Stegman, 1996; Montes-Helu et al. 2009). The U.S. Forest Service (USFS) and collaborators are working on the Four Forest Restoration Initiative (4FRI), a forest restoration project to increase forest resiliency to fire and reduce the threat of catastrophic wildfire (USDA, 2011). Although not a goal of 4FRI, studies have shown that water yield can be increased as a result of forest thinning (Hewlett and Hibbert, 1967; Bosch and Hewlett 1982; Zou et al., 2010). Several 4FRI alternatives are expected to slightly increase water yield in areas where vegetation treatments remove 25 to 50% of overall tree canopy cover within a given watershed (4FRI EIS Phase 1). These increases will likely only be temporary.

1.2.2 - Flagstaff Watershed Protection Program

Two forested areas at-risk for catastrophic wildfire near the City of Flagstaff will not be addressed by 4FRI due to high costs, presence of threatened species, and inaccessible terrain: the Dry Lake Hills area and Mormon Mountain (Figure 5). These areas have non-market-supported treatment costs due to low timber value and steep terrains, but the damages that could result from a catastrophic wildfire and post-fire flooding would be devastating to the City (City of Flagstaff, 2012). The Dry Lake Hills are drained by Schultz Creek, Switzer Canyon, and Spruce Avenue Wash which are tributaries of the Rio de Flag that could flood and cause billions of dollars of damage in the aftermath of a severe wildfire.

Mormon Mountain is located within the Upper Lake Mary Watershed which feeds the largest surface water source for Flagstaff, supplying 50% of the city's drinking water. If the watershed were to burn, the reservoir would receive abundant ash and sediment, degrading the water quality to a level unfit for consumption. The costs of reengineering the water treatment plant or, alternatively, drilling more deep groundwater wells to compensate for the lost reservoir would both be expensive, each estimated to cost over $20 million (Burke, 2012).

The Dry Lake Hills area is located in steep mountainous terrain north of the City and partially feeds the Rio de Flag watershed that runs through Flagstaff. Vegetation is a mix of ponderosa pine and mixed conifer type with over-dense structure and doghair thickets throughout. There is high recreational use of this area with an extensive trail system, and camping and rock climbing areas (City of Flagstaff, 2012). If one-fourth to all of this area were to burn, the risk of post-fire flooding in the Rio de Flag could be 2 - 6.6 times larger than the 100-year discharge (Figure 6) (Leao, 2005). Floods of these

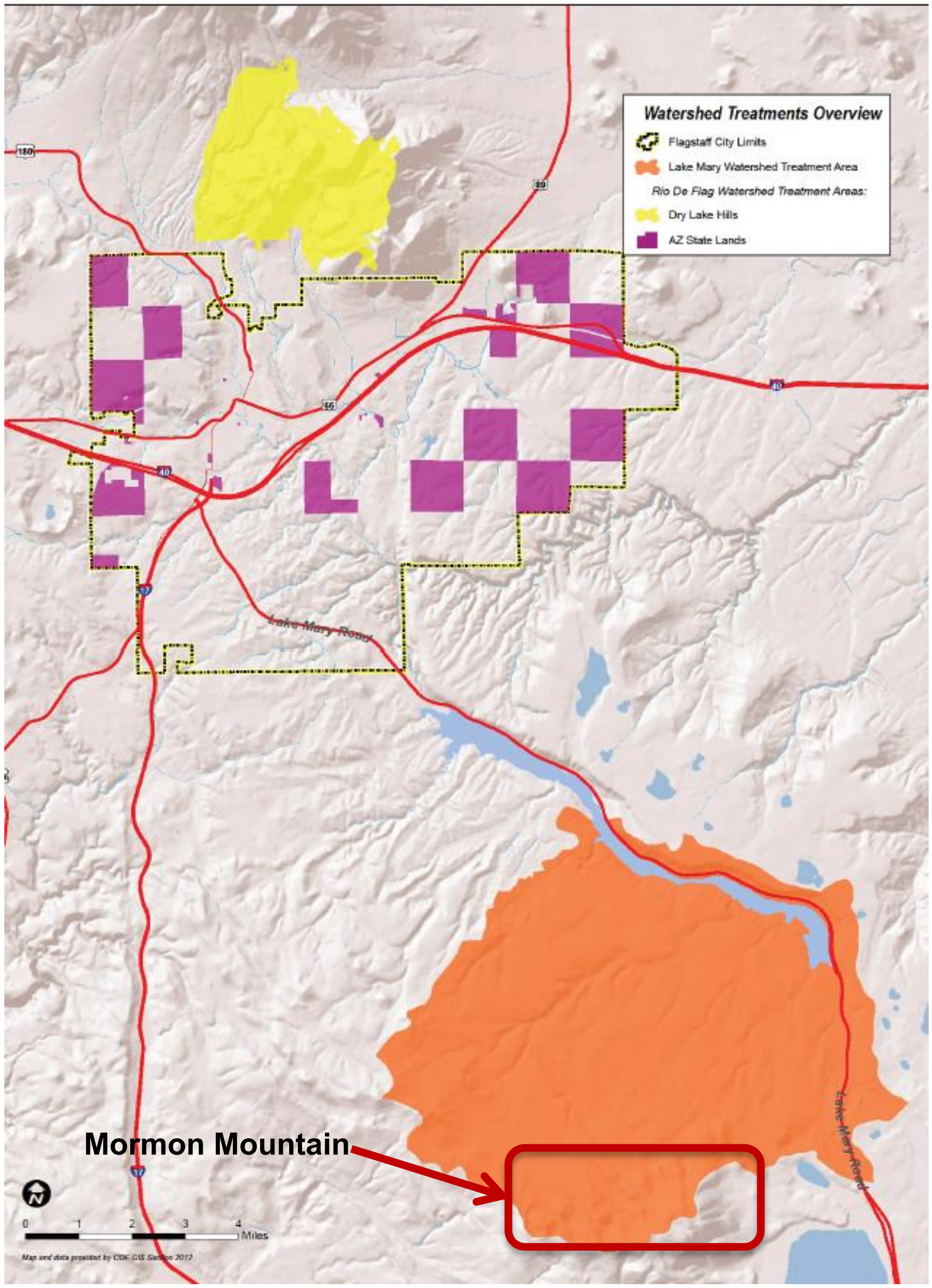


Figure 5. Flagstaff Watershed Protection Project (FWPP) treatment area map. Dry Lake Hills project area (yellow) and Mormon Mountain in the Lake Mary Watershed (orange). (Protect Our Watersheds/Support #405)

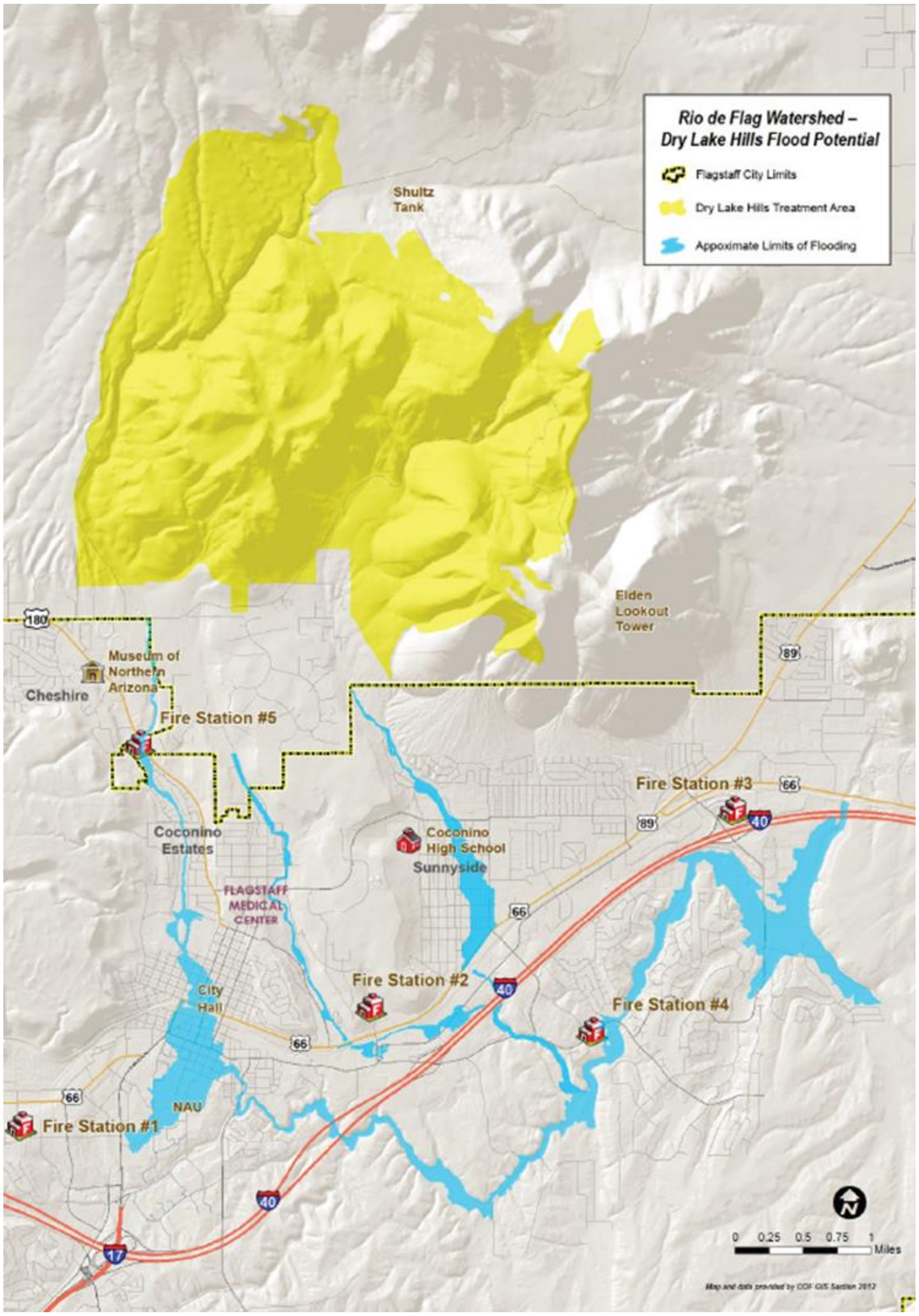


Figure 6. Estimated extent of 100-yr post-fire flood in Flagstaff. FWPP Dry Lake Hills area watershed (yellow). (Protect Our Watersheds/Support #405)

high magnitudes and the associated debris flows and sediment laden-sheet flows could inundate downtown Flagstaff businesses, homes, and city and campus facilities.

1.2.3 - Ballot Question #405

The City of Flagstaff and collaborators devised Ballot Question 405 which proposed use of a $10 million bond as a mechanism to pay for forest thinning in Lake Mary Watershed and Dry Lake Hills area. The staggering cost predictions of damages that could be caused by a wildfire and post-fire flooding, in conjunction with the legitimate risk of catastrophic wildfire, illustrated to residents by the Schultz Fire, help to justify the price of the bond. The bond received a 73% “yes” vote from City of Flagstaff voters in the November 6th, 2012 general election (Coconino County, 2012). Planning for restoration began immediately, with thinning slated to begin in the summer of 2015 (The City of Flagstaff, Arizona and the Flagstaff Ranger District, Coconino National Forest, 2012). The approval of this bond has policy significance and indications for the future of Collaborative Forest Landscape Restoration Programs (CFLRP). A CFLRP is restoration work on National Forest land that is achieved by cooperation between the USFS and other stake holding entities. There have been a few cities that have conducted restoration on forest service land using municipal funds, such as Santa Fe and Denver, but Flagstaff is the only known city to use *voter approved* municipal funds to thin trees on USFS land (Margolis et al., 2009).

The results of the November 2012 elections are indicative of a major shift in attitudes about forest management and fire mitigation. Thinning and prescribed burning was first conducted by the Greater Flagstaff Forest Partnership (GFFP) in collaboration with the City in 1996. There was a lot of public criticism, both about the aesthetic result of thinning (people weren't used to an open forest) and about the costs of the project. The initial implementation of fuels reduction and prescribed burning for one acre was a $50,000 project, a high cost compared to today's more efficient treatment options. The Forest Service was accused of masking a profitable logging program as fuels reduction treatment to leverage taxpayer dollars (Friederici, 2003). Since that preliminary project there has been public outreach and education about the risks of fire suppression and the importance of thinning the over-dense modern forests. The increase of severe wildfires all over the Southwest, particularly the proximal Schultz Fire, has likely aided in shifting public understanding of fires and the reality of the risks to Flagstaff citizens, increasing public understanding of and support for the bond.

1.2.4 - Flagstaff Watershed Protection Project Treatments

The general goals of the FWPP are to reduce the canopy closure from up to 100% down to 40-70%, reduce stems per acre from 10-5218 down to 300 or less, and to reduce the dead and down fuel load from up to 50 tons/acre to 3-7 tons/acre in ponderosa pine, and 10-15 tons/acre in mixed conifer. The FWPP Proposed Action summary (City of Flagstaff and Coconino National Forest, 2013) outlines several treatment alternatives. The treatments for Schultz Creek watershed include ponderosa pine, mixed conifer, Mexican Spotted Owl protected activity centers (MSO PAC's), and designated "no treatment" areas, each of which has a different prescription in the proposed action plans.

Alternative 1 is "No Action," in which projects that were initiated prior to FWPP planning will continue, but no new thinning with occur as part of FWPP. Jack Smith Schultz treatments, a timber contract that predates FWPP, are currently being executed in parts of the Schultz Creek watershed.

Alternative 2 is "Proposed Action with Cable Logging Emphasis on Steep Slopes" which has an emphasis on cable logging wherever plausible. In the Schultz Creek watershed, this will include prescribed fire (with both initial slash pile burning and broadcast burning) with mechanical thinning and hand thinning. In MSO PACs, trees greater than 16 inches dbh will be mechanically thinned and will contribute more than 50% of the final stand basal area. At least 40% canopy cover will be maintained. Trees up to 9 inches dbh will be hand thinned. In ponderosa pine and mixed conifer stands outside the MSO PACs, treatments will result in uneven-aged structure, with a mosaic of openings occupying 30-60% of the area. Alternative 3 is "Proposed Action without Cable Logging," similar to alternative 2 but without cable logging, reducing the need to remove large trees and snags on steep slopes. Helicopter logging would be required for some exceptionally steep and rocky areas.

Alternative 4 is the "Minimal Treatment Approach". This is designed so that only the absolute minimum amount of treatment required to meet the purpose of the project will be administered. Only selected areas with dense fuel loading where topography aligns with prevailing winds will be treated due to the higher probability of wildfire. This treatment is a minimal treatment alternative designed to placate potential objections from some collaborating agencies, and is unlikely to be selected (Erin Phelps, personal communication, 11/19/13).

1.3 - RESEARCH

1.3.1 - Introduction

This study is a characterization of the potential sediment response to post-fire precipitation in Schultz Creek, an 8,500 m channel within an 18 km^2 watershed within the Dry Lake Hills area on the Coconino National Forest north of Flagstaff (Figure 7). The

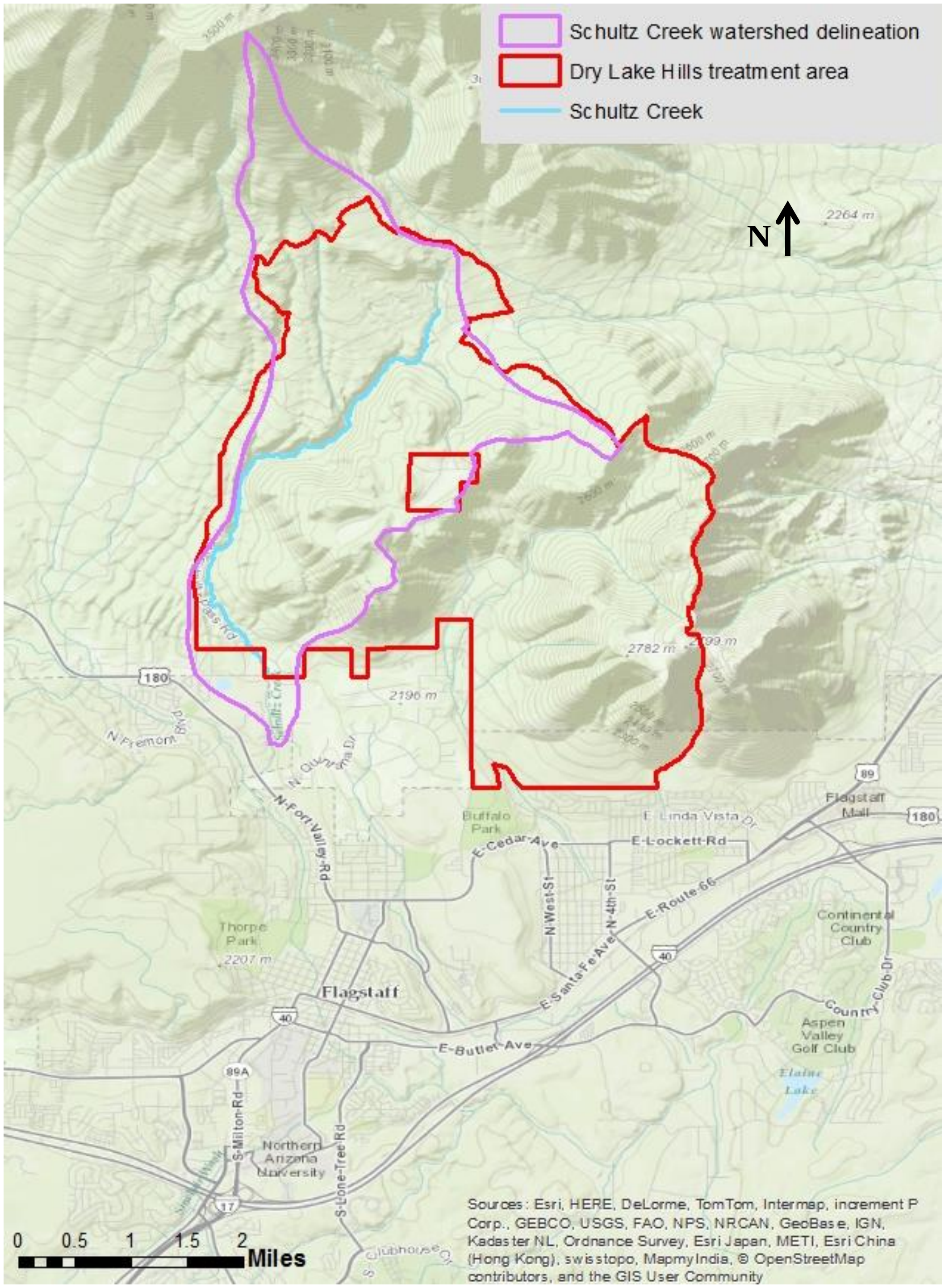


Figure 7. Schultz Creek Watershed within the Dry Lake Hills area. Schultz Creek is directly north of the City of Flagstaff.

Schultz Creek Watershed is not in the Schultz Fire Burn area, which was in the Weatherford Canyon watershed located northeast of Schultz Creek (Figure 8). Sediment response was examined with surficial mapping and development of an alluvial chronology to understand historical sediment response, and by modeling channel hydraulics and sediment transport that could result from post-fire precipitation events using HEC-RAS. Models simulated sediment transport in the axial channel following a fire that could occur in both current forest conditions, and in predicted post-treatment forest conditions. These methods test the hypothesis that post-fire sediment yields will be significantly reduced by forest thinning treatments, and that sediment yields will be significantly higher post-fire. Surficial deposits along Schultz Creek were mapped by Holm (1988) cumulatively as undifferentiated alluvium, talus, till, and colluvium, providing minimal detail for distribution of types of alluvium and neglecting potential geomorphic differences in surficial deposits.

1.3.2 - Objectives and Significance

The objectives of this study are to: (1) increase the understanding of the specific hydrologic responses of this watershed to fire and forest restoration, (2) provide a tool (hydraulic flood model) that can be adapted by the City for ongoing analysis of the effectiveness of restoration and could be used to improve design of emergency treatments in the event of a fire, (3) create publicly accessible, research based evidence for flood risk mitigation through forest restoration over time, and (4) develop a methodology that can be utilized by other communities that could be impacted by fire in forested watersheds, both at the Wildland-Urban Interface (WUI) and in downstream communities that may

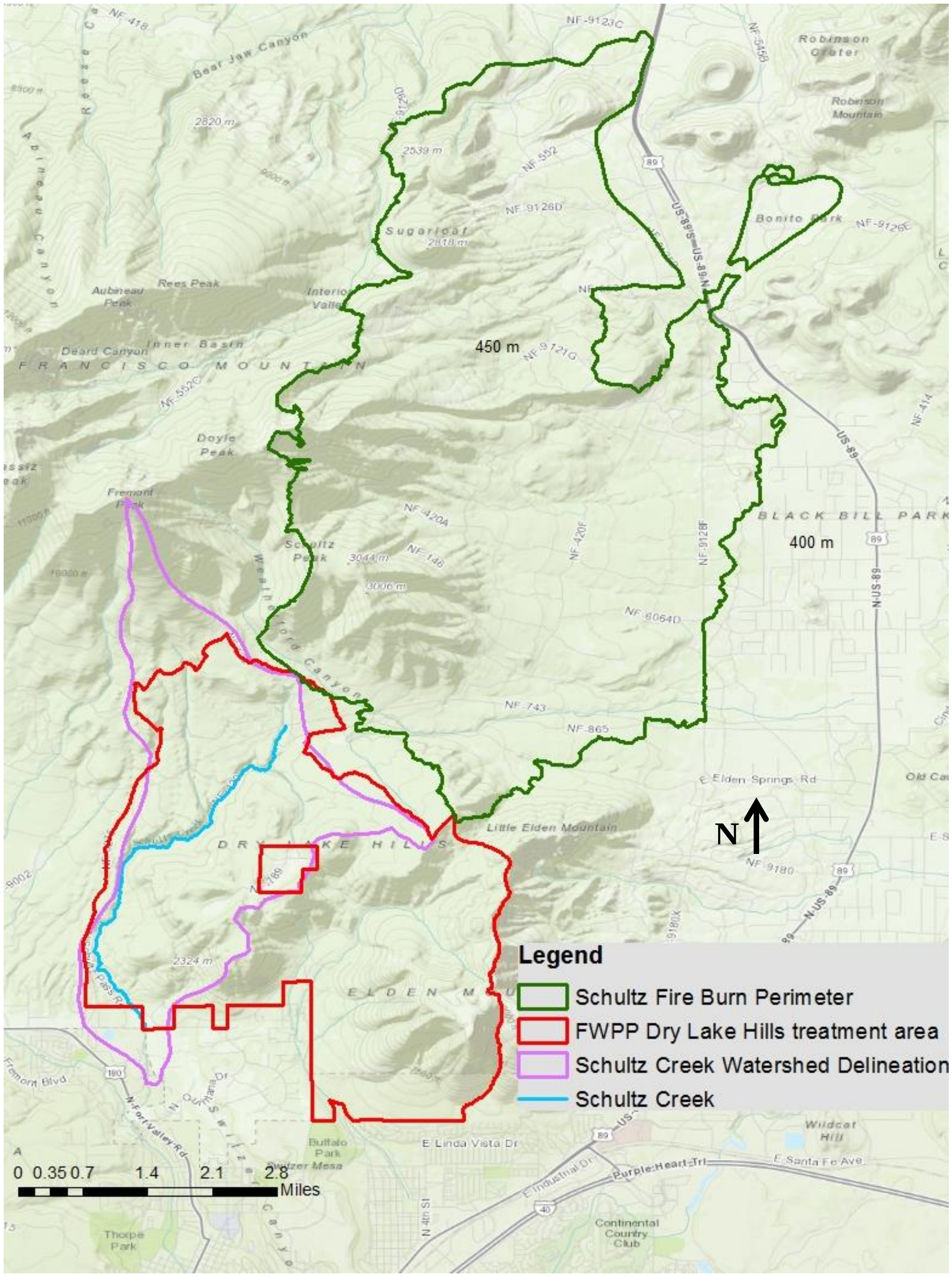


Figure 8. Map of Schultz Burn area and Schultz Creek watershed. The Schultz Burn area is northeast of the Schultz Creek watershed. See Figure 3 for Schultz Fire soil burn severities and flooding.

benefit from resources made available by forested watersheds. This project is not only an important element of Flagstaff's forest restoration program, but can be used as a tool in other communities attempting to adapt land management practices to reduce natural hazards of forested watersheds. Proven methods and results will encourage other communities to proactively address forest health issues that impact their watersheds.

The lack of historical data on flooding for the Dry Lake Hills area watershed severely limits understanding of specific watershed responses to post-fire flooding and sediment discharge. There has been no surficial mapping of geomorphic units or fluvial deposits along the channel that presumably contain a high percentage of the sediment that could be mobilized during high magnitude runoff events. Forest Service soils are mapped in the Terrestrial Ecosystem Survey (TES), a systematic classification of terrestrial ecosystems according to their climate, geology, soils, and possible natural vegetation. The TES uses the current version of the National Cooperative Soil Survey Standards, similar to soil surveys conducted by the Natural Resource Conservative Service (NRCS). The NRCS is a branch of the USDA that maps soil, but typically only on private land. TES information is available from the Forest Service Region 3 Geospatial Data website. Components with similar attributes are often grouped together, limiting the resolution of the survey in some locations. Mapping was initially conducted by stereoscopic analysis of 1:24,000 aerial photographs and any general data available on soils, vegetation, geology, and geomorphology. More data were gathered in the field for at least one 375 m^2 (4036 ft^2) plot for each component of each map unit at sites deemed undisturbed. However, most current digital maps were created by digitizing from the original aerial photography-based delineations (Runyon, 2014). Due to the mapping scale, the natural complexity of soil ecosystems can be inadequately represented by the TES. Studying the past soil record and mapping the area will improve understanding of sediment mobilization potential of the watershed, which is invaluable information for predicting potential impacts of erosion and sediment transport to the City of Flagstaff in the event of post-fire flooding.

The results of the alluvial chronology combined with the hydraulic modeling can be used to determine the degree of damage to city infrastructure that could be caused by floods in forest conditions following treatment. This thesis is informative to the City of Flagstaff as it continues to plan and execute forest thinning. The results are also valuable to the public, particularly the voting stakeholders, providing metrics to measure the success of the Flagstaff Watershed Protection Project. Voters are interested in cost avoidance, or 'money saved' by thinning the forest, which could be loosely quantified in a follow up economic analysis by estimating the per taxpayer cost of damage by post-fire flooding and mass wasting in comparison to reduced flooding effects in response to forest thinning. As thinning progresses and watershed responses can be measured, a well-constructed hydraulic model can be more finely calibrated and used throughout the project as a tool for the city and a deliverable to citizens for their investment.

1.4 - PREVIOUS WORK

1.4.1 - Alluvial Chronology

Alluvial chronologies are studies of the preserved record of fluvial activity in a channel. Alluvial chronologies are developed using a variety of data and field observations, but almost always include analysis of fluvial terraces and terrace deposits. The methods used depend largely on the research question, the fluvial environment, and the existing data that are available. Terrace landforms are common features along channels in incised valleys, providing some understanding of the timing and location of entrenchment and/or aggradation, and sometimes the hydrologic and climatic conditions through time (Connell et al, 2007; Pederson et al., 2006; Pazzaglia et al., 1998). A terrace is a relatively flat surface that indicates a former water level, often running parallel to the active channel, and typically bounded on one side by an ascending slope and the other side by a descending slope (Connell et al., 2007). Several different types of terraces have been catalogued by various researchers who have identified the implications of different terrace forms (Zonneveld, 1975; Bull, 1991). The materials beneath a terrace are termed “alluvial fill” or “deposits”, and the thickness of these deposits depends on the paleohydrology of the channel (Connell et al., 2007).

There have been many different alluvial chronology studies in the arid and semi-arid southwestern United States, utilizing a variety of methods and focusing on different factors influencing alluvial activity. Connell and others (2007) mapped five inset levels of Pleistocene fluvial deposits of the Rio Grande in New Mexico, inferring that former and present positions of the channel are differentiated between two separate locations. The stratigraphy and grain size compositions of fluvial deposits and geochemistry of a tephra deposit allowed researchers to distinguish the Rio Grande’s different formations, identify periods of aggradation, and analyze changes in stream power, sediment supply, and climate over time. Pederson and others (2006) used fill terraces to determine periods of aggradation and rates of bedrock incision of an eastern portion of the Colorado River during the middle to late Quaternary. The terraces were dated using optically stimulated luminescence, uranium series, and cosmogenic nuclide dating. Numerical dating of terrace deposits is particularly useful for determining bedrock incision rates.

Hereford has completed many alluvial studies in the Northern Arizona region (Hereford, 1984; Hereford, 2002). Hereford (1984) developed an alluvial chronology of the Little Colorado River to study the aggradational and erosional events during the 20th century, focusing on the influence of climate on the geomorphology and depositional dynamics of channels. Hereford used historical discharge data, historical mean annual precipitation and temperature data, vegetation data including ring counts, aerial photographs, presence and form of geomorphologic features, stratigraphy and sedimentology of flood plain deposits, and dendrochronology of salt cedar. Although at the time of the study there was limited consensus about how climate modifies alluvial channels, Hereford concluded that most of the recent changes in the channel morphology resulted from climate fluctuations.

Joyal (2004) analyzed alluvial stratigraphy of two drainages on the Mogollon Rim in central Arizona utilizing mapping, descriptions, and C^{14} dating of terraces and other alluvial features. The study indicates that recent incision in his study area was unprecedented during the mid to late Holocene, and that a major erosional event occurred approximately 6000 yr B.P., possibly driven by a regional climatic phenomenon termed the Holocene Thermal Maximum. Valleys have been gradually aggrading until recent major incisional events (1970±70 years B.P., and 390±90 years B.P.) at Mogollon Rim study sites), recorded and studied in numerous locations in Northern Arizona (Hereford, 2002; Neff et al., 2003; Anderson et al., 2003). This collection of research suggests that mid-Holocene valley aggradation began later at sites closer to the Mogollon Rim, and appears to have been initiated progressively earlier as you move northward. In Walnut Canyon, about 130 km north of the Mogollon Rim and 17 km east of Schultz Creek, C^{14} dating of alluvial fill reflected initiation of aggradation around 8,000 years B.P. (Neff et al., 2003).

1.4.1.1 - Longitudinal Profiles

The formation and preservation of terraces result from changes in stream activity over time, from incision to lateral erosion to alluvial aggradation (Pederson et al., 2006). The behavior of a stream is dependent upon the balance between the stream power and resisting forces preventing sediment transport. The shape of a longitudinal profile can be used to infer where a channel is dominated by erosion or aggradation and can indicate locations of significant sediment storage (Pederson et al., 2006; Pazzaglia et al., 1998). Steeper portions of the profile indicate less sediment accumulation, while shallower portions of the profile indicate more sediment accumulation. Longitudinal profiles are often used as a component of alluvial chronology analyses.

1.4.1.2 - Post-fire Hydraulic Modeling Challenges

Estimating sediment transport, erosion, and aggradation, is notoriously challenging in ephemeral channels following wildfire. The hydrologic and sedimentary responses to wildfire are predominantly a function of burn severity and precipitation (Robichaud et al., 2000). Sediment availability is one of the major controls on rates of erosion, and sediment flux on hillslopes is the greatest source of increased erosion following wildfire (Canfield et al., 2005). Wildfire increases sediment availability by exposing bare soil and by elimination of stabilizing root structures, increasing erodibility. The variability of burn severity results in a high degree of spatial heterogeneity across a watershed of soil infiltration rates and erodibility, complicating predictions of sediment availability (Moody et al., 2013; Scott, 2006).

The spatial and temporal variability of precipitation in arid and semi-arid regions, particularly on watersheds with high relief, further complicates post-wildfire sediment response (Moody et al., 2013; Scott, 2006; Smith et al., 2011). Erodibility on burned watersheds does not have a linear relationship with rainfall intensity (Moody et al., 2013; Yatheendradas et al., 2008).

Abnormally high runoff rates are common on recently burned watersheds, causing higher and flashier peak flows that increase bedload and suspended sediment capacities, often resulting in hyperconcentrated flows (Robichaud, et al., 2000; Scott, 2006). Hyperconcentrated flows are non-Newtonian in nature, meaning that they have a much higher transport capacity for sediment than Newtonian flow (Scott, 2006). Most current methods used to predict sediment transport were developed for perennial flow, and assume Newtonian flow, which is defined by Scott (2006) as a linear relationship between the shear stress from fluvial action and the resulting rate of shear upon sediments. Many transport formulas are also designed to predict equilibrium sediment transport in steady uniform flow (Hummel et al., 2012). Sediment transport in ephemeral channels, even prior to disturbance from fire, is generally unsteady, also known as nonequilibrium transport, also described as "step-wise" by Scott (2006). This means that fluvial sediments do not respond immediately to changing flow conditions, there is often a lag time, resulting in pulses of sediments as opposed to continuous sediment transport (Hummel, et al., 2012; Moody and Martin, 2009). Responses to fire will also vary depending on regional factors including climate, terrain, and vegetation, and the few predictive sediment transport formulas that have been developed for ephemeral flow conditions are not widely applicable, generally only appropriate for individual regions (Scott, 2006; Moody et al., 2013).

Predicting the magnitude, location, and route of sediment transport is very important for preventing hazards to communities adjacent to watersheds prone to fire and post-fire flooding, and to mitigate potential environmental impacts. Flashy discharge poses risks to life and property due to high magnitude flow, rapid time to peak flow, and high sediment concentrations in floodwaters (Robichaud, et al., 2000; Yatheendradas et al., 2008; Smith et al., 2011; Hummel et al., 2012; Scott, 2006). Water quality in reservoirs, lakes, and riparian zones is degraded by suspended sediments carried by floodwaters. This can be damaging to aquatic organisms and municipal water users (Robichaud et al., 2000). Floodwaters with high sediment concentrations exert increased force on flow routing and flood retention structures, heightening potential for damage (Scott, 2006; Hummel et al., 2012). Post-fire sediment concentrations also have impacts on the channel morphology which can lead to damages to property on or near the channel. Aggradation increases with larger suspended bedloads, which can elevate the channel floor and/or constrict the channel, increasing the potential for overbank flooding (Hummel et al., 2012).

1.4.1.3 - Sediment Transport Models

There are several models capable of modeling hillslope sediment yield, such as the Revised Universal Soil Loss Equation (RUSLE) (Nyman, et al., 2013), Erosion Risk Management Tool (ERMiT) (Elliot et al. 2001), and Disturbed Water Erosion Prediction Project (WEPP) (Elliot et al. 2001), which are commonly used by land managers primarily to predict annual erosion from burned landscapes. However, because annual erosion modeling was not the objective of this study these standard models would not be useful. There are several models, such as Kineros2, that have been used to predict or simulate post-fire sediment transport in ephemeral channels, but are utilized much less by land managers. Some have data requirements or resolutions that preclude them from being used in this study.

Kineros2 (Goodrich, et al., 2012) is an event-based watershed rainfall-runoff and erosion model that has been successfully calibrated for pre- and post-fire hillslope erosion and sediment transport in channels in the arid Walnut Gulch experimental watershed near Tucson, AZ (Canfield and Goodrich, 2006) and at Starmer Canyon near the 2011 Las Conchas Fire, NM (Canfield et al., 2005). Kineros2 is used with the ArcGIS-based Automated Geospatial Watershed Assessment (AGWA) tool, which automates watershed delineation and performs initial parameterization of watershed elements using national GIS data layers, such as land use/land cover, digital elevation model (DEM), etc. Routing of overland flow is achieved by solving a one-dimensional (1-D) kinematic wave equation using a finite difference method. Although this model is described as appropriate for watersheds from plot scale (<10 m^2) to large watersheds (1,000 km^2), the watershed elements are estimated as planes and trapezoidal channels with no curvature and limited topographical resolution, which has been found to induce excess infiltration and distort runoff patterns and sediment fluxes (Lopes and Canfield, 2004). Kineros2 would only be able to very coarsely estimate the Schultz Creek topography and would likely underestimate sediment yield. The model has only been validated for watersheds that are several hundred km^2 with robust data sets. Nationally available ground cover data would also be insufficient for describing the Schultz Creek watershed due to lack of fine-scale surficial mapping and potentially inaccurate approximation techniques of national ground cover surveys. Precipitation inputs for Kineros2 are typically from rain gauge observations, of which there are none in the Schultz Creek study area. Ten or more rainfall-runoff-sediment events are recommended for calibration and validation of the model which are not available for the study area. This is also not the best model for this study due to its limited use. Not only should a model accurately simulate ephemeral flood flows, it should be accessible to Forest Service personnel and City of Flagstaff land managers to improve future utilization of the model generated by this study.

HEC6T is a sediment transport model that has been used to describe changes in channel scour and deposition in ephemeral channels after the 2000 Cerro Grande Fire in northern New Mexico. The Cerro Grande Fire was in a semi-arid watershed forested with ponderosa pine and having volcanic dacite substrate, incredibly similar to Schultz Creek (Canfield et al., 2005; Earles et al., 2004). Since Canfield et al. (2005) and Earles et al. (2004) studies, HEC6T has been incorporated into HEC-RAS (USACE, 2006a), an open-source hydraulic modeling program that is widely used and recognized by federal agencies and local governments. Scour and deposition is described at cross sections, and reaches are defined between cross sections. Physical parameters such as grain size distributions and Manning's roughness coefficients can be entered manually for each cross section and defined for each reach, increasing the amount of field data that can be incorporated into a model. The cumulative volume change in sediment is highly dependent on slope as defined by the sediment transport equation by Yang (Yang and Wan, 1991), deemed one of the most appropriate equations for post-fire sediment transport in ephemeral channels along with Engelund-Hansen (Canfield et al., 2005; Yang and Wan, 1991; Hummel et al., 2012). HEC-RAS has the capability of modeling sediment transport in quasi-unsteady flows, also termed nonequilibrium transport, which is typical of post-fire flows on burned watersheds (Hummel et al., 2012).

1.4.3 - Previous Local Modeling

There have been several projects conducted to model the flooding risks of the Rio de Flag as a result of high-magnitude precipitation (ADWR, 1988; Arizona Engineering Company, 1979; City of Flagstaff, 1991; FEMA, 1995; Hill et al., 1988; USACE, 1975; USACE, 2000). The most recent study with the highest quality data was performed by the US Army Corps of Engineers (2000) to delineate the floodplain for the Rio de Flag to determine potential economic damages of flooding. Discharges for several different storm recurrence intervals (2-yr, 10-yr, 25-yr, 50-yr, 100-yr, 500-yr) were determined at six major concentration points along the Rio de Flag using HEC-2 and HEC-RAS. The closest concentration point to the Schultz Creek watershed is the northern-most concentration point which lies on the Rio de Flag downstream of the confluence of Schultz Creek, concentration point one (Figure 9). The Army Corps of Engineers' (COE) results indicate that most of the Rio de Flag channel within city limits only has a capacity for the 10-year peak discharge, which was modeled as 451 ft^3/s at concentration point one. Maps of the 100 and 500 year flood plains depict the extent of the inundation in downtown Flagstaff and the NAU campus (Figure 10). Modeled discharges for the 100 and 500 year flood at concentration point one were 1,910 ft^3/s and 4,830 ft^3/s, respectively. The COE hydrologic model utilized limited historic flooding information from USGS gauges, stage data from recent floods, surveyed high water

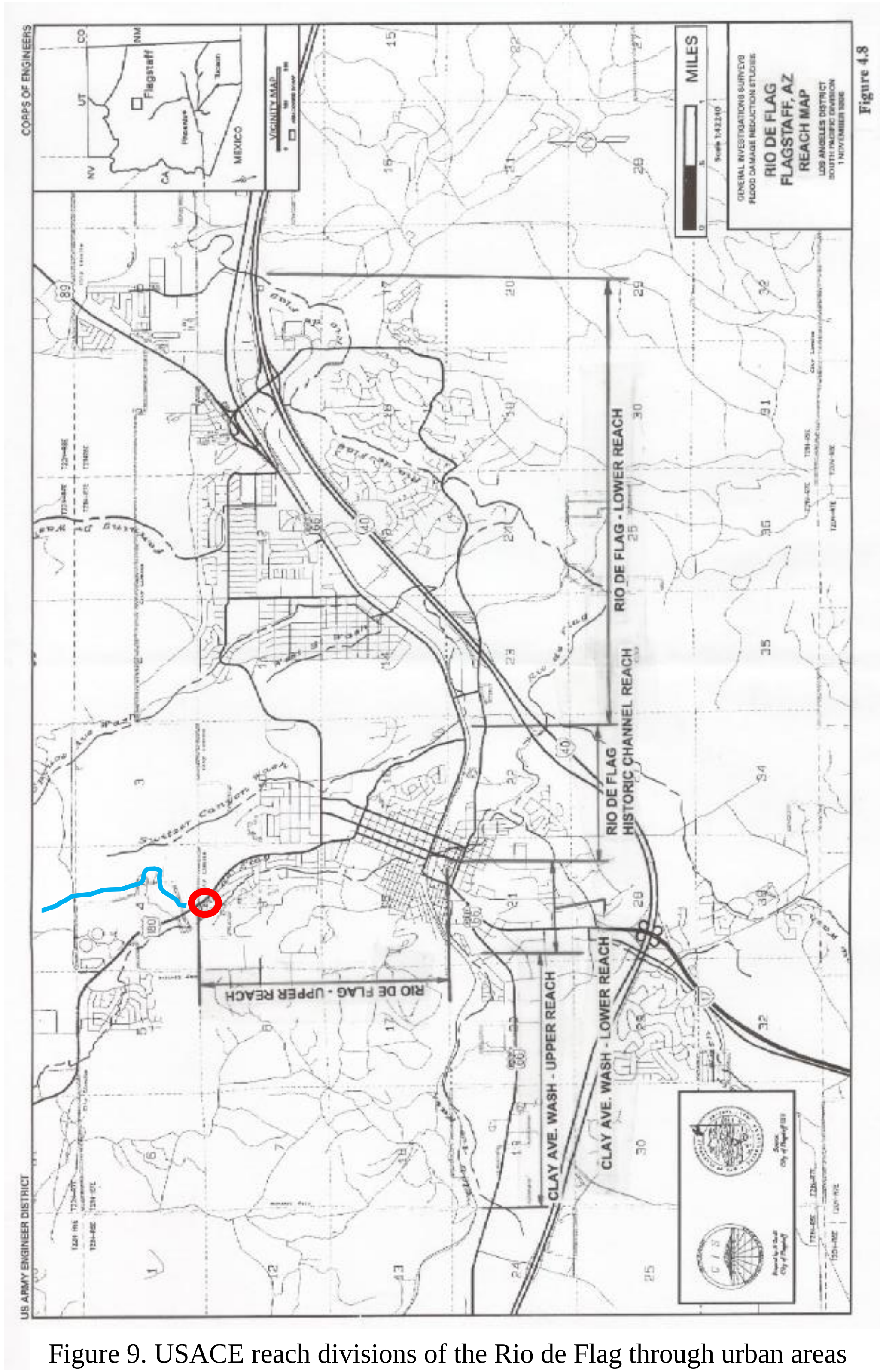


Figure 9. USACE reach divisions of the Rio de Flag through urban areas of Flagstaff. Concentration point one annotated with red circle, bottom of Schultz Creek annotated with blue line (USACE, 2000).

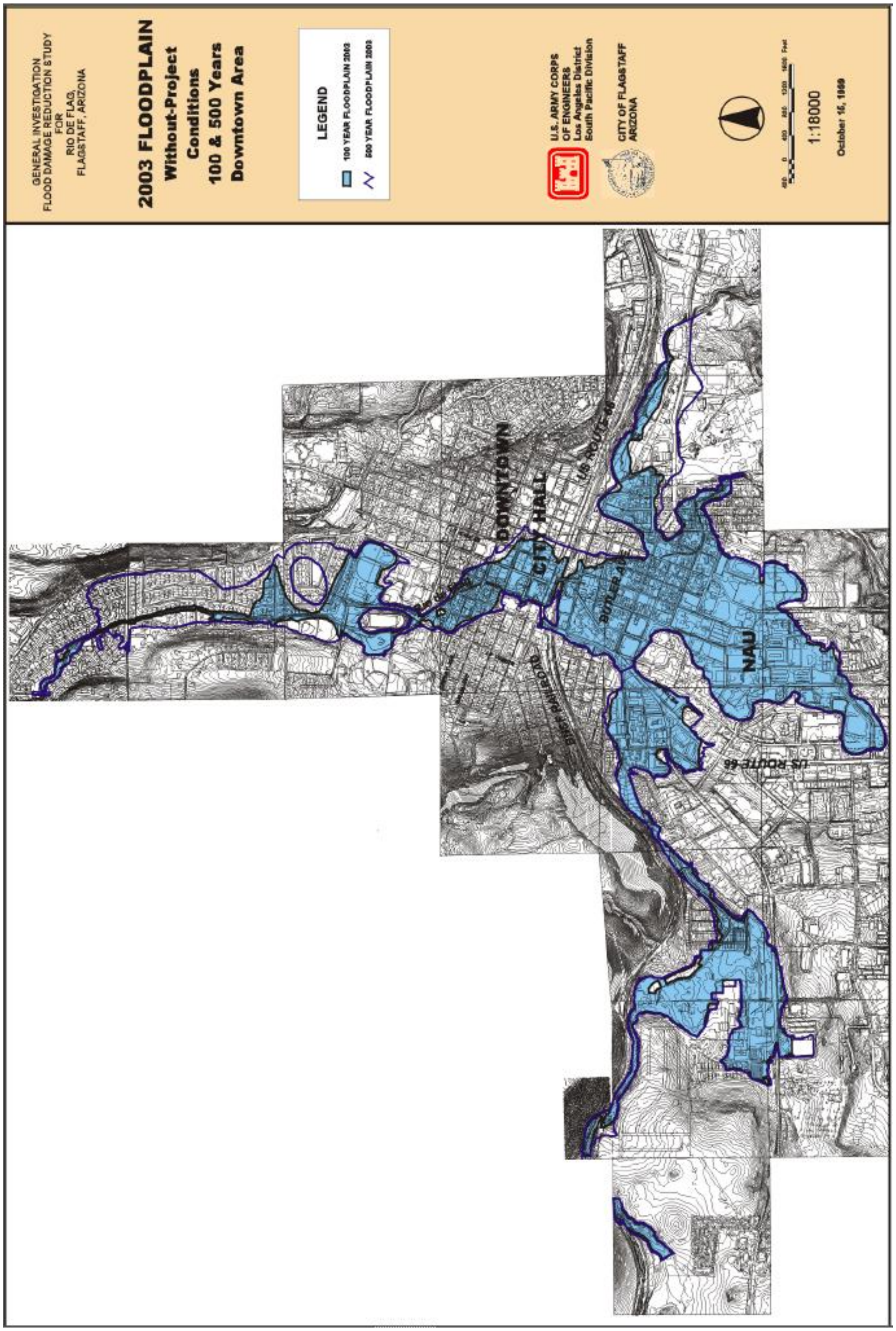


Figure 10. USACE modeled 100 and 500 year flood plains in downtown Flagstaff (USACE, 2000).

marks from the most recent flooding event in 1993, and associated rainfall data. Two-foot contour interval topography was used.

Leao (2005) determined a detailed water budget for the Upper Rio de Flag watershed using hydrologic data from flood plain information studies by the U.S. Army Corps of Engineers (1974) and a USGS study that established a stream gauging network for Flagstaff (Hill et al. 1988). Leao (2005) used this to predict the effects of forest treatment and wildfire in the Upper Rio de Flag watershed. Thinned conditions were based on the assumption that 6,000 ha of forested areas of the Rio de Flag would be treated to the intensive level executed by the GFFP (13.8 m^2/ha remaining basal area tree density) within 3 years of the study. Three generic wildfire scenarios were created related to watershed area burned at high severity, including burning over one-fourth, one-half, and the entire watershed area. A 10 m Digital Elevation Model (DEM) was used for topographic input. National Resource Conservation Service (NRCS) hydrologic soil groups were used to describe infiltration rates of soil types. Infiltration rates were decreased by 40% of the original rate to simulate wildfire based on experiments suggesting that infiltration rates decrease up to 40% post-fire due to hydrophobicity of burned soils (Robichaud et al., 2000). HEC-HMS (USACE, 2006b), a program designed to determine surface runoff from a watershed, was used to estimate the amount of runoff from the watershed based on daily precipitation events recorded by the Fort Valley Weather Station from 1910-2002. Within HEC-HMS, the NRCS rainfall-runoff model was selected to determine the event based runoff from thinning and wildfire under dry, average, and wet moisture conditions. The NRCS Curve Number model estimates precipitation excess as a function of total event precipitation, soil cover, land use, and antecedent moisture conditions.

Leao's results showed that catastrophic wildfire could increase peak discharge by 2 to 6.6 times the historic 100-year discharge, which occurred in 1923 (Figure 11). The 1923 Rio de Flag flood resulted from a 25-year storm recurrence interval with 5.92 cm rainfall depth producing a 100-year flood with 34 m^3/s discharge (about 1200 f^3/s). While Leao's study is a strong indicator for the increase of peak discharge as a result of forest thinning, it does not inform how post-fire peak discharges could be affected by changes in forest conditions in the Dry Lake Hills area. NRCS soil types are based on very coarse resolution soil data for the area aerial photos which were later digitized (1:24,000 aerial photography). The NRCS method was developed using data collected from a large part of the United States, possibly leading to poor predictions for runoff in local conditions. See section 1.3.2 for more detailed discussion of NRCS and TES soil data. Improved soil maps would increase the precision and accuracy of runoff rate predictions for different precipitation events. At the time of Leao's study, neither 4FRI nor the Flagstaff Watershed Protection Plan existed, therefore thinning scenarios modeled by Leao did not include predictions for changes in forest condition based on these newer forest restoration treatment plans.

The only known sediment routing models for the region have been created post-burn (e.g. JE Fuller, 2011; Natural Channel Design, 2012), which is an indication of the data deficiencies for the Rio de Flag watershed and the surrounding drainages. The data used to predict flooding in previous models such as Leao (2005) and USACE (2000) provide relevant baseline information about flooding risks on the Rio de Flag, but are not high enough resolution to be appropriate for modeling in this project. There have been no studies dedicated specifically to flooding and erosion risks of the Schultz Creek watershed.

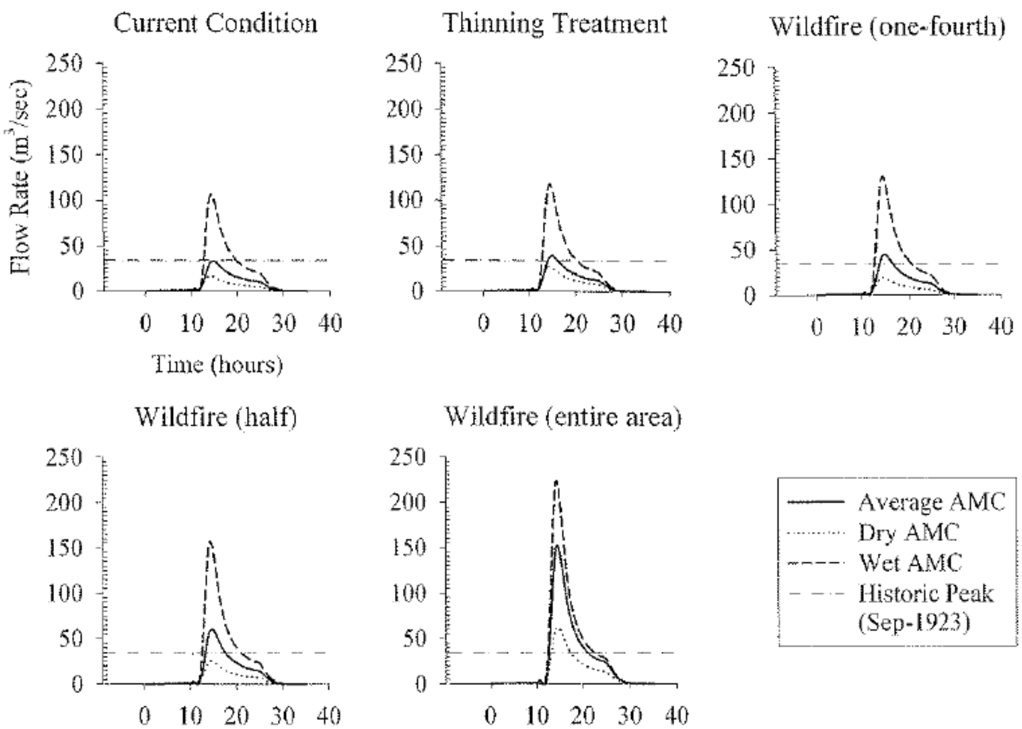


Figure 11. Hydrographs from modeling results from Leao (2005) for a 100-year storm event under all forest density and wildfire scenarios.

Chapter 2 - Alluvial Chronology and Analysis of Available Channel Sediments

INTRODUCTION

Ephemeral channels are very common in the arid and semi-arid southwestern U.S., making up over 81% of all streams. Arizona contains the highest overall percentage of ephemeral channels in the southwest at 94% (Levick, et al., 2008). Ephemeral channels are incredibly important components of ecosystems in arid and semi-arid climates. Humans rely on the water that is filtered through these channels when they function properly.

Ephemeral channels are delicate systems with idiosyncratic fluvial responses to precipitation when compared with more widely studied and well understood perennial stream systems. These channels are very sensitive to changes in vegetation that can be caused by local or short-term natural disturbances, global climate change or human disturbances. Ephemeral channels rarely ever reach equilibrium between aggradation and erosion; they are constantly shifting between phases (Bull, 1997). Fluxes in local base level result from shifts between phases; erosion causes a drop in base level, and aggradation causes a rise in local base level. Both processes are self-perpetuating, but can be simultaneously occurring at different reaches of channel allowing occasional, brief attainment of equilibrium between the processes.

Understanding ephemeral channel sediment response to wildfire, particularly in steep terrains such as in Schultz Creek, is very complicated. The hydrologic and sedimentary responses to wildfire are predominantly a function of burn severity and precipitation (Robichaud et al., 2000). Spatial and temporal variability of precipitation in arid and semi-arid regions becomes even less predictable from orographic lifting in mountainous regions (Moody et al., 2013; Scott, 2006; Smith et al., 2011). Burn severity is also very spatially heterogeneous. Sediment availability is one of the major controls on rates of erosion, and sediment availability is increased by wildfire by exposing bare soil and eliminating root structures (Canfield et al., 2005).

Surficial mapping does not exist for the Schultz Creek channel. Surficial deposits of uplands were mapped by Holm (1988) cumulatively as undifferentiated alluvium, talus, till, and colluvium, providing minimum detail for distribution of types of alluvium and neglecting potential geomorphic distribution in surficial deposits. To understand how Schultz Creek sediments would be affected by post-wildfire flooding and how forest restoration could mitigate potential erosion, detailed study of channel sediment deposits was necessary. An alluvial chronology was developed to understand pre-historic fluvial and morphological influences on the watershed, and how the current morphology came to be. In the event of a wildfire, appropriate selection of emergency response erosion mitigation treatments would be made possible by historical analysis of the channel and up-to-date knowledge of stored sediments (Carroll, 2011). Lack of such information could be part of the reason some BAER treatments failed on the Schultz Burn area in 2010. In some cases, erosion mitigation treatments ended up contributing to erosion and flooding damage (Neary et al., 2011).

This work is not just important for increasing the breadth of knowledge of Flagstaff hydrology and geomorphology, but is a contribution to the body of work focused on understanding the causes of historic and modern erosional cycles and how they are linked to climate and human activities. Literature suggests that humans have impacted watersheds in the region in complex ways (Hereford, 1984) and could continue to do so if a heightened understanding of the cascading effect of human activities is not achieved.

2.1 - METHODS

Various field and laboratory methods were utilized to accomplish the objectives of this study. The methods related to alluvial chronology and analysis of available channel sediments included soil analysis, surficial mapping, radiocarbon dating of macroscopic charcoal, and cross section measurement.

2.1.1 - Trench Site Selection

The primary criterion for selecting trench sites was the potential for repeated fluvial deposition. Reconnaissance was focused on identifying small alluvial fan deposits within the channel, partially by the morphology of a deposit and partially based on the proximity to tributaries that may have acted as zones of sediment transport. A secondary factor was the presence of recent incision, which facilitates the trenching process and possibly indicates the exposure of older and better preserved sediments. The main channel in the uplands and on the watershed's main alluvial fan was considered for trench locations.

2.1.2 - Trench Excavation

Photographs of the trench site and the surrounding geomorphology were taken prior to digging. Digging was initiated at the top of the channel bank and the stratigraphic soil column was exposed perpendicular to the channel floor. To reduce the impact to the channel, the trenches were not vertically continuous when the channel banks were sloped. The trenches were "stepped off", meaning that vertical trench sections were kept as close to the channel bank slope as possible. This resulted in terraced trenches (Fig. 12). All efforts were made to keep the trench sides at right angles

Figure 12. Photographic example of the trenching process. Trench 1, 1.4 m total depth. White lines show how right angles were maintained during “stepping off”, yellow dotted ovals show flagged nails marking boundaries between soil units, and yellow hexagon shows flagged nail marking location of charcoal sample.

to the vertical sections to improve recognition of the stratigraphy and structure of the soil deposits. Trenches extended from the top of the channel bank or terrace (when present) down to the channel floor, or as close as possible when large boulders were present in the deposits.

Charcoal samples were collected during the final stages of trench excavation. After large volumes of sediment and soil were displaced, a hand trowel was used to make angles between trench faces more precise and closer to right angles. The hand trowel was used to extract charcoal samples in situ without touching the samples, which can contaminate the charcoal with other sources of carbon. Samples were transported and stored in aluminum foil pouches. The depths of the charcoal samples were recorded and the precise locations were marked with flagged stakes and photographed (Fig. 12).

Once a trench was fully excavated and the charcoal selected, a large paint brush was used to remove loose sediment to improve visibility of any depositional structures. Distinct soil units were identified based on differences in color, structure (clay or sand lenses, hyperconcentrated flow deposits, etc), sorting, gravel content, induration, and any other distinguishing features. Boundaries between soil units were marked with flagged nails and then described in detail and measured (Fig 12). Particular attention was paid to presence of gravels and pebbles, relative concentration of charcoal, and presence or lack of structure. Each soil unit was photographed, as well as any notable features. The entire trench was photographed with soil unit and charcoal sample stakes. Approximately 0.5 liters of soil was sampled from each unit for laboratory analysis, and the depth of the sample within each unit was recorded. All excavated sediment was replaced and duff pressed into the soil surface before leaving the site to minimize erosion of exposed soil.

2.1.3 - Surficial Features

2.1.3.1 - Debris Flows

Charcoal was sampled from several debris flows for radiocarbon analysis to determine if the debris flows dated to a single high-flow event, or several different events. To ensure that sampled charcoal was transported by the debris flows, samples were taken from soil underneath large boulders (Fig 13). Boulders were determined to have been stable based on degree of burial and the presence of lichens. Fines from the surfaces of the debris flow deposits had likely been reworked by fluvial processes over time, evidenced partially by boulders protruding from the deposits. Sediment on the surface or within several inches of the surface could not be sourced to the debris flows with confidence.

2.1.3.2 - Terrace Deposits

Terrace depositional units were identified during trench site reconnaissance. Terraces were defined as relatively flat surfaces running parallel to and elevated above the modern channel but below the flood plain.

2.1.3.3 - Knick Points

Several different types of knick points were identified during reconnaissance and later systematically surveyed. The size of the knick point and the material in the channel resulting in the knick point were considered relevant information that would help to interpret depositional and fluvial characteristics of the channel. Anything less than ¼ meter change in elevation was not catalogued.

2.1.4 - Sediment Analysis

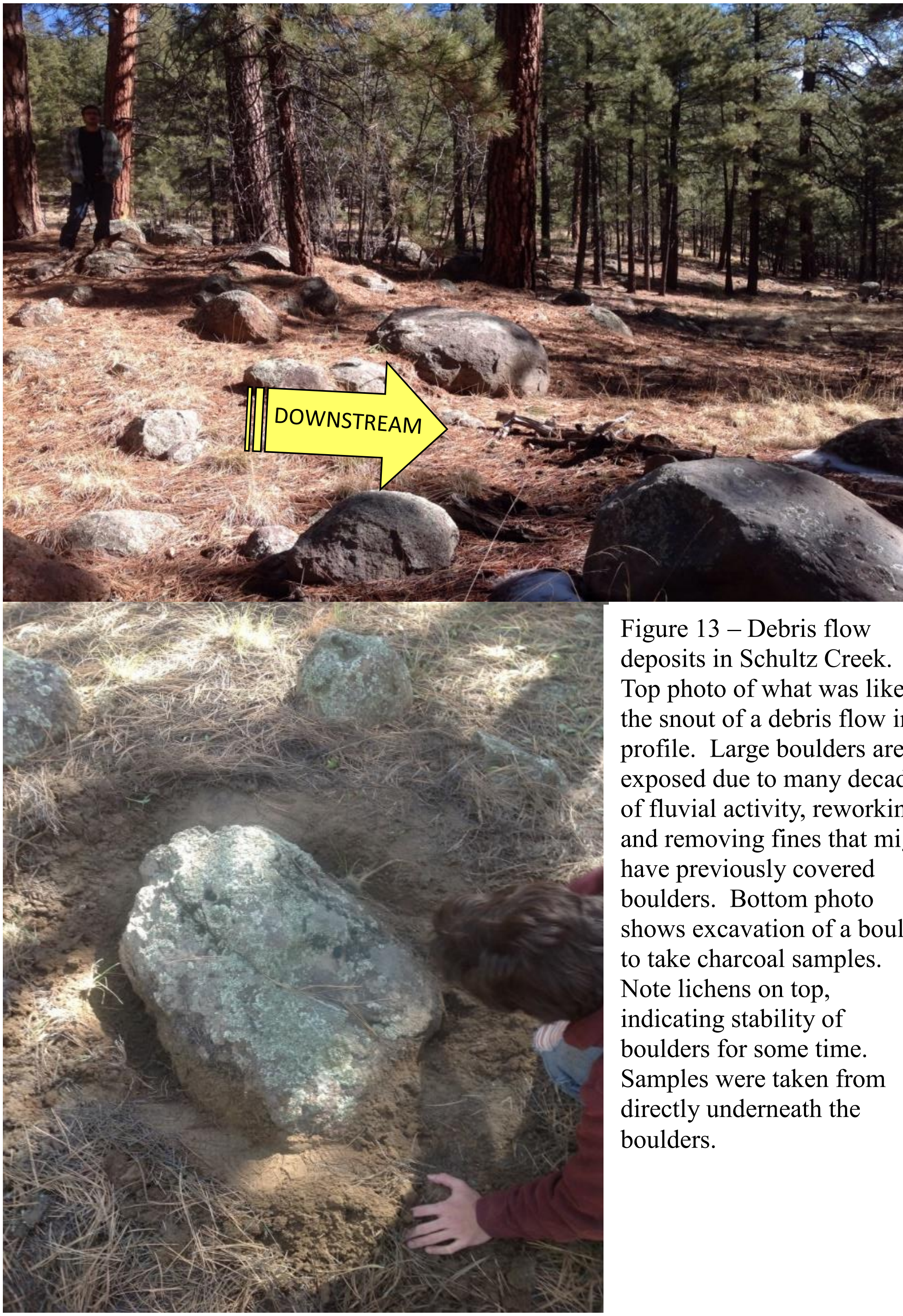


Figure 13 – Debris flow deposits in Schultz Creek. Top photo of what was likely the snout of a debris flow in profile. Large boulders are exposed due to many decades of fluvial activity, reworking and removing fines that might have previously covered boulders. Bottom photo shows excavation of a boulder to take charcoal samples. Note lichens on top, indicating stability of boulders for some time. Samples were taken from directly underneath the boulders.

Soil samples were analyzed for color, texture, and grain size. Sieve analysis was used to determine the percentage of coarse material (>2 mm) in each soil unit. Texture was analyzed according to standard procedures (Kellogg, 1937) using the fraction of fines after the coarse grains (> 2mm) had been separated. A Munsell color chart was used to identify the dry color of the fine fraction of the soil (<2 mm). Fresh surfaces of dry peds were also tested with dilute HCl to test for carbonate development, but no samples reacted with the acid. The presence of charcoal fragments was qualitatively evaluated during sieving.

2.1.5 - Radiocarbon Analysis

Selected charcoal was limited to sub-angular to angular wood fragments. Initially, the intent was to collect and date charcoal fragments from a fire event large enough to be represented in sediments throughout the watershed. Radiocarbon dates of sediments that have remained in place since the time of fire can yield information about fire return intervals in a watershed and, in the context of the sediment stratigraphy, post-fire depositional characteristics. Burned seeds, needles, and twigs are most reliable for determining a fire recurrence interval due to their low residence time on the landscape. Other characteristics of fire-related deposits are high concentrations of large, angular charcoal, distinct layers of burned litter or soil, and dark charcoal mottling (Jenkins, 2007).

Sample ages were obtained through Accelerator Mass Spectrometry (AMS) ^{14}C dating, analyzed at the National Science Foundation-University of Arizona AMS facility and the UC Irvine Keck Carbon Cycle AMS Facility. Samples were preprocessed by standard acid-base wash methods to remove post-carbonization organics such as humics.

Samples were then combusted and graphitized prior to carbon isotope measurement. Measured AMS ^{14}C were calibrated to calendar years before present (cal yr B.P.) with Calib 7.0 (Stuiver and Reimer, 1993) and reported with two-sigma age ranges.

2.1.6 - Sediment Volume

Sediment volume was determined by finding the difference in area between detailed channel cross sections and approximate valley cross sections of the buried bedrock surface assumed to underlie the sediment stored in the channel, the terrace deposits, and the flood plain.

Channel cross sections were measured by hand with measuring tapes and a hand bubble level. Measuring tapes were stretched across the channel perpendicular to the thalweg and the bubble level used on one bank directed at the equivalent elevation on the opposite bank to level the measuring tape. A cross section was measured approximately every 250 m of channel, with additional cross sections when a 250 m mark coincided with a major knick point to document the differences in channel morphology directly upstream and downstream of knick points. The widths of the cross sections were determined in the field to capture the terraces and their depositional units (when present) and a small portion of the flood plain (when present). Depths were measured at least every 50 cm of width using a measuring tape, with additional measurements where complex topography was present. Depths are accurate to the nearest 0.5 cm. Locations of the cross sections were recorded on the GISPro (v. 2.1.1) app (Garafa, LLC, Provo, UT) on an Ipad 4. Geomorphic units in cross sections were defined, and terrace elevations above the modern channel were noted. At each cross section, Manning's N was determined visually for the channel floor, channel sides, and channel banks using Chow's (1959) roughness coefficient values for natural streams.

Valley cross sections were approximated by determining the steepest slope of the valley walls at the same locations of measured channel cross sections and extending them into 'V' shape beneath the channel cross section (Fig 14). Bedrock in alluvial channels in steep terrain is assumed to erode into a 'V' shape. Images from debris flows off the 2010 Schultz Burn area show low-order channels with this morphology (Figure 4b). The valley cross sections with aerial LiDAR coverage were measured using ArcMap. Valley cross sections without LiDAR coverage were measured manually using a Topcon Laser Level and stadia rod. Vertical (elevation) controls were established at ground locations as near as possible to the channel cross section locations using a Leica CS25 Global Navigation Satellite System (GNSS) receiver. The GNSS receiver was configured to provide a Real-Time Network (RTN) kinematic GNSS positions using cellular data service provided by Verizon, for access to the Arizona Continuously Operating Reference Station (AZCORS) network. The nearby AZCORS station AZFL, located on the NAU campus, was utilized. GNSS-determined ellipsoid heights were reduced to NAVD88 (North American Vertical Datum 1988) elevations using the GEOID09 model.

To estimate the total sediment available to be mobilized in the Schultz Creek channel, each two-dimensional sediment profile was assumed to be constant along a length of channel bracketing each cross section. Each cross section was considered the midpoint for its length of channel.

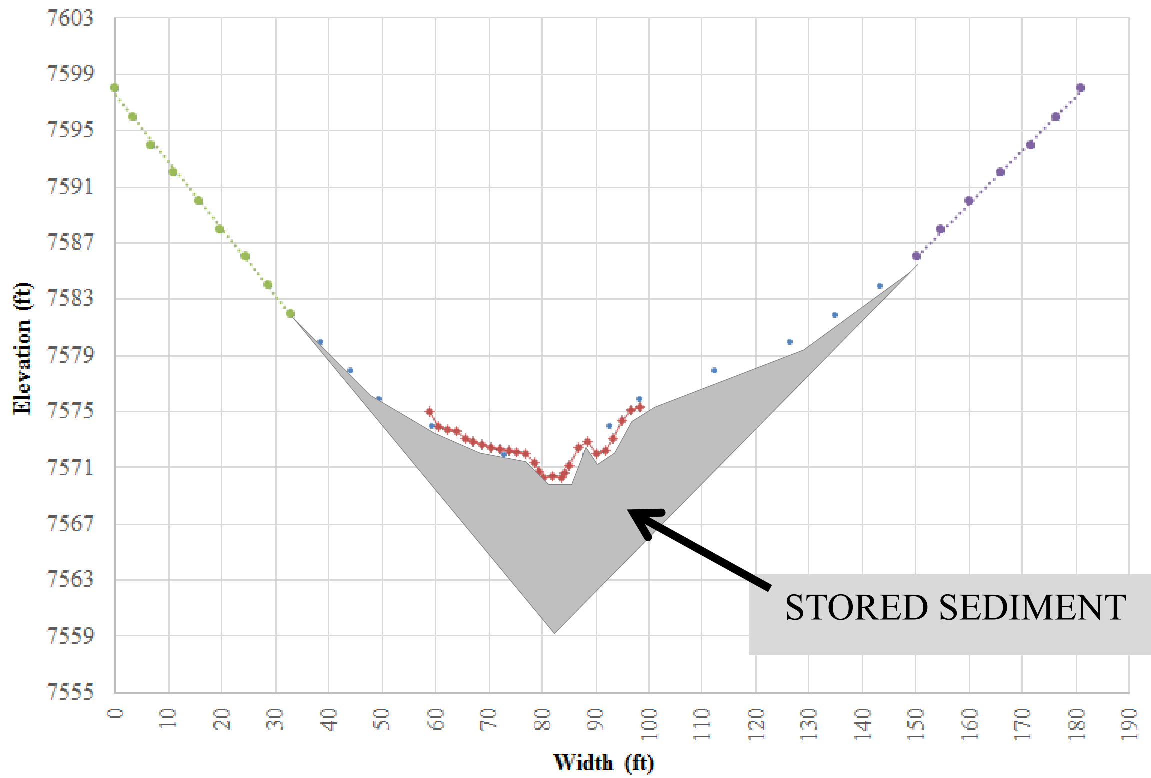


Figure 14. Illustration of sediment volume graphical method for cross section 10. Green and purple circles mark the valley wall slopes and were extrapolated into a V shape below the active channel. The red triangles are from the channel cross section measurements.

A soil bulk density is required to convert sediment volume to sediment mass for comparison with other published sediment storage estimates. Sandy loam soils below the top 2.5 cm of sediment in northern Arizona are documented having bulk densities ranging from 1.34 to 1.79 g/cm^3 (Heidmann and Thorud, 1975). The median was used for the approximate bulk density of soils in Schultz Creek (1.57 g/cm^3) since the actual soil bulk density of sediment in Schultz Creek is not known.

2.1.7 - Longitudinal Profile

A longitudinal profile is a plot of elevation against distance along the channel. The type of equation (exponential, logarithmic, power, etc.) fitting a profile has been shown to reflect something about the grain size distribution along a profile, or what controlling variable has a dominant influence on profile form (Knighton, 1984) A concave longitudinal profile shows that a channel is in an erosional phase, whereas a convex longitudinal profile reflects a depositional phase. If a longitudinal profile is neither convex nor concave, the channel is in a brief state of equilibrium in which erosion and deposition are in balance (Bull, 1997). Equilibrium is very briefly, if ever, achieved. Disequilibrium is more common due to changes in base level; entrenchment causes lowering of local base level, and deposition raises local base level. Both processes are positive feedback mechanisms (Bull, 1997). Different sections of a channel can be in different phases simultaneously, and equilibrium is achieved when these reaches meet or cross.

A longitudinal profile was derived in ArcMap using 61 cm (2 ft) contours from LiDAR provided by the City of Flagstaff and 30.5 cm (1 ft) contours from LiDAR provided by Coconino County. City LiDAR was collected aerially in April, 2013 by

Sanborn Mapping. The root-mean-square error of elevation of all points did not exceed 15 cm (Sanborn, 2014). Specifics about the County LiDAR is currently unknown. A point was plotted in ArcMap every 50 m of channel, measured using the ruler tool. The elevation at that point was estimated based on proximity to known elevation contours.

2.1.8 - Surficial Mapping

A surficial map depicting the spatial extent of major geomorphic features (the modern channel, depositional units 1 and 2, the flood plain) was created for a section of each subreach of the main channel. The location for each surficial map was selected to map the locations of trenches and charcoal sampling. Navigation in the field was done using the GISPro app on the Ipad4, and surficial maps were drawn on paper in the field and later digitized in ArcMap. Precise locations of cross sections were marked with rebar in the field, and were used to determine exact location of surficial map with respect to cross sections. Surficial maps were sketched manually on ArcMap printouts with cross sections and LiDAR as reference.

2.2 - RESULTS

The axial channel of Schultz Creek was divided into five subreaches (Fig. 15) to develop a conceptual model for each section of the channel (Fig. 16 – 20). Subreaches were defined based on differences in soil analyses, terrace deposits, valley width, channel slope, and field observations of channel expression, vegetation density, channel substrate, and other distinguishing surficial features such as debris flow deposits and knick points (Table 1).

2.2.1 - Geomorphology

2.2.1.1 - Terrace Deposits

Alluvial fan deposits were more prevalent in the lower portions of the drainage. Relief of the watershed increases towards the headwaters, and in many places the channel is confined by steep bedrock walls, and more likely to be zones of transport than zones of deposition. The few locations where there appeared to be terrace development indicated consistent deposition and relatively stable geomorphology, and were therefore deemed most appropriate as trench sites. Seven trench sites were selected, six of which were along the axial channel, with one on a less active tributary near base level (Trench 4) (Fig 15). Trench 4 was selected because of its location on the main alluvial fan and due to the channel's well entrenched morphology.

Two terraces are intermittently present along the channel, the deposits of which are referred to as Unit 1 and Unit 2. When both terraces are present (generally in the lower portion of the watershed), the terrace surface of Unit 1 is elevated higher above the modern channel than the terrace surface of Unit 2, therefore Unit 1 was initially assumed to be the older unit. At some locations, the modern channel floor is the same elevation as the lower terrace, indicating that there has been no incision of Unit 2 at that location, likely due to less steep slopes. In some reaches at higher elevations, steep bedrock walls constrain the lateral movement of the channel and no terraces have been able to develop.

Physical characteristics of the depositional units changed throughout the watershed, although some major distinctions can be made based on sediment analyses (table 2), surficial mapping (figure 21-25), and general field observations (table 1).

Unit 1 is fairly consistently present throughout the entire watershed, with the exception of locations where valley walls are too narrow to allow for significant terrace

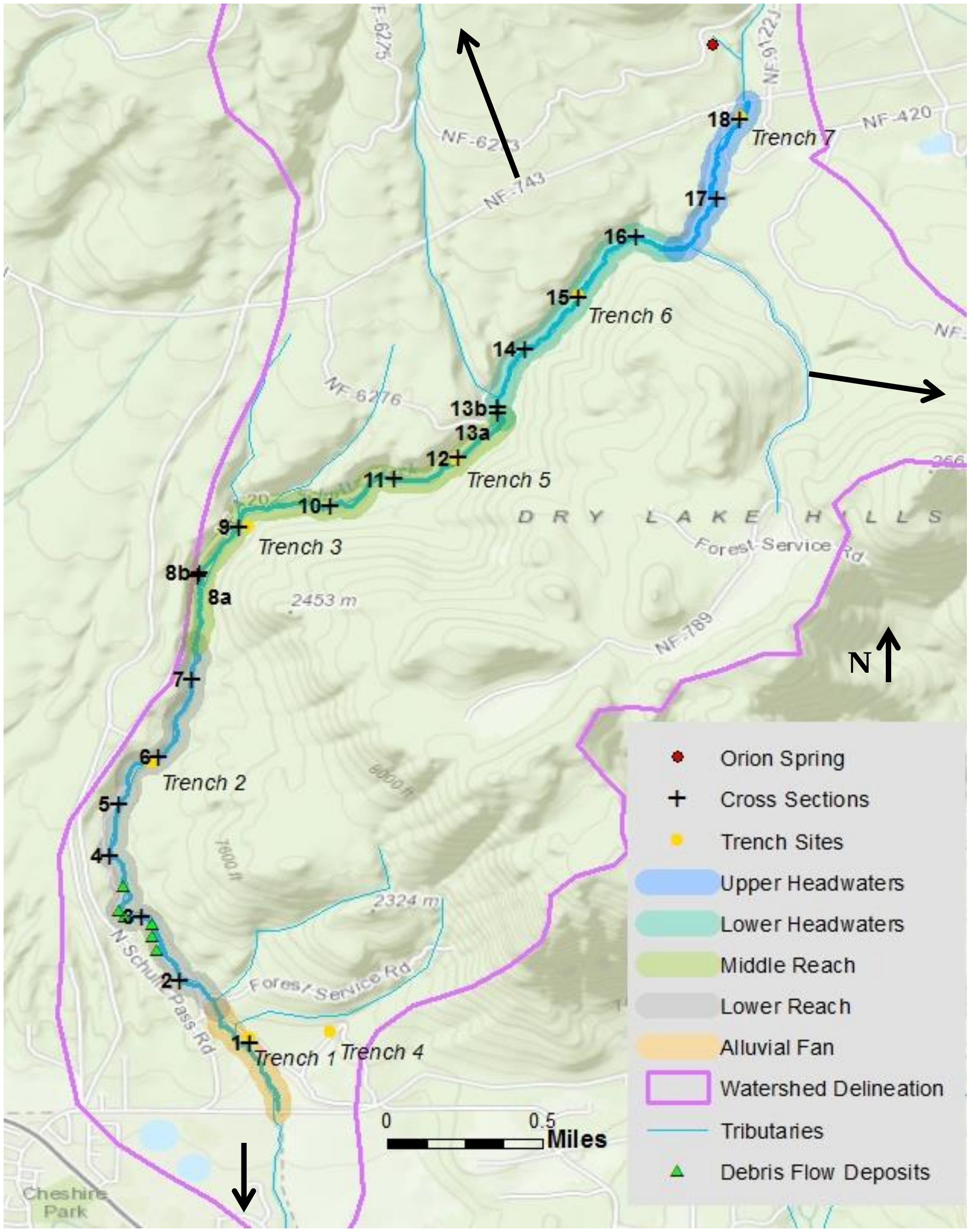


Figure 15. Sub-reach map of Schultz Creek with trenches and channel cross sections. Arrows indicate that watershed extends out of map frame. See figure 27 for full watershed extent.

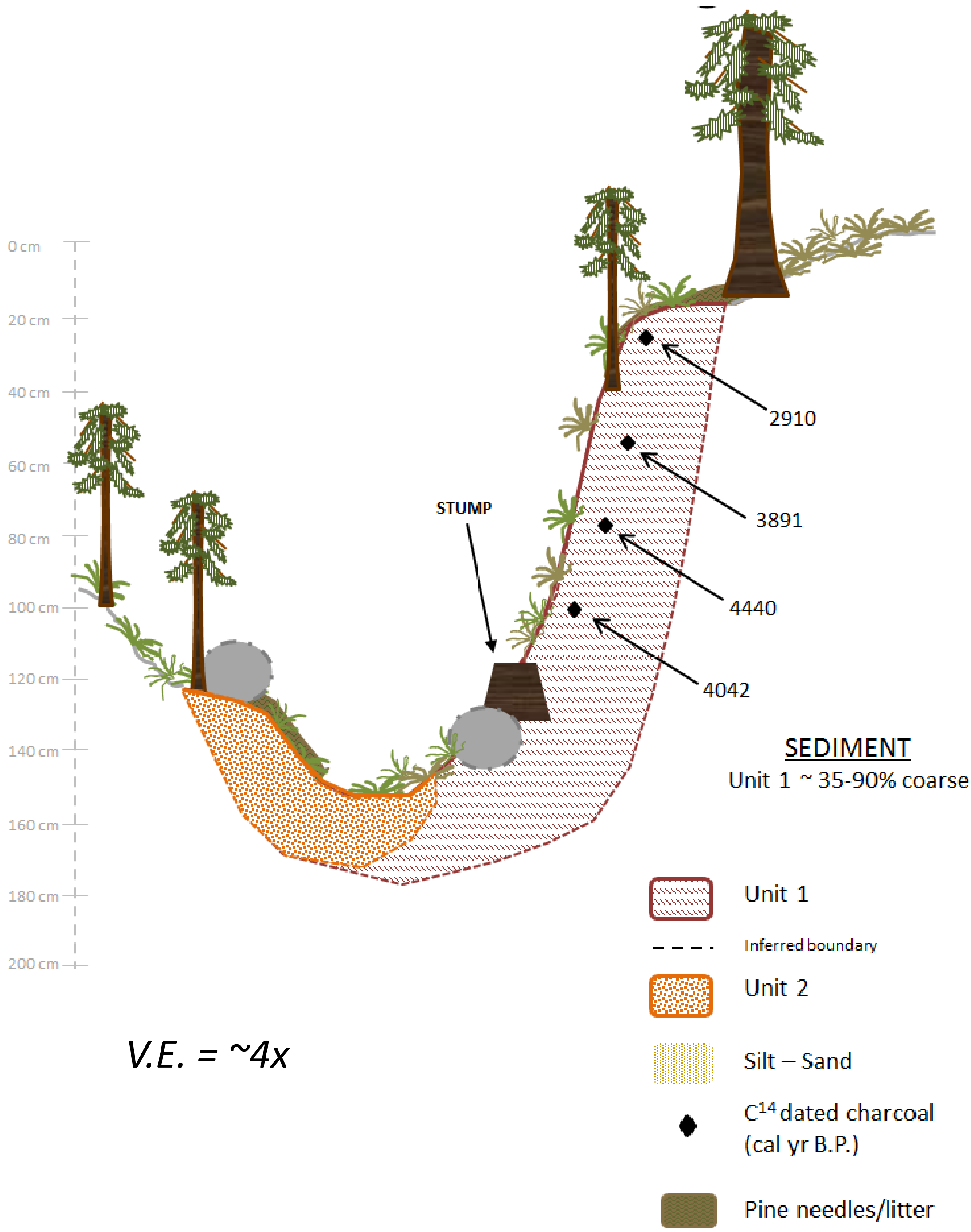


Figure 16. Conceptual diagram of Upper Headwaters subreach of Schultz Creek (see figure 15 for location). % coarse is sediment >2mm diameter.

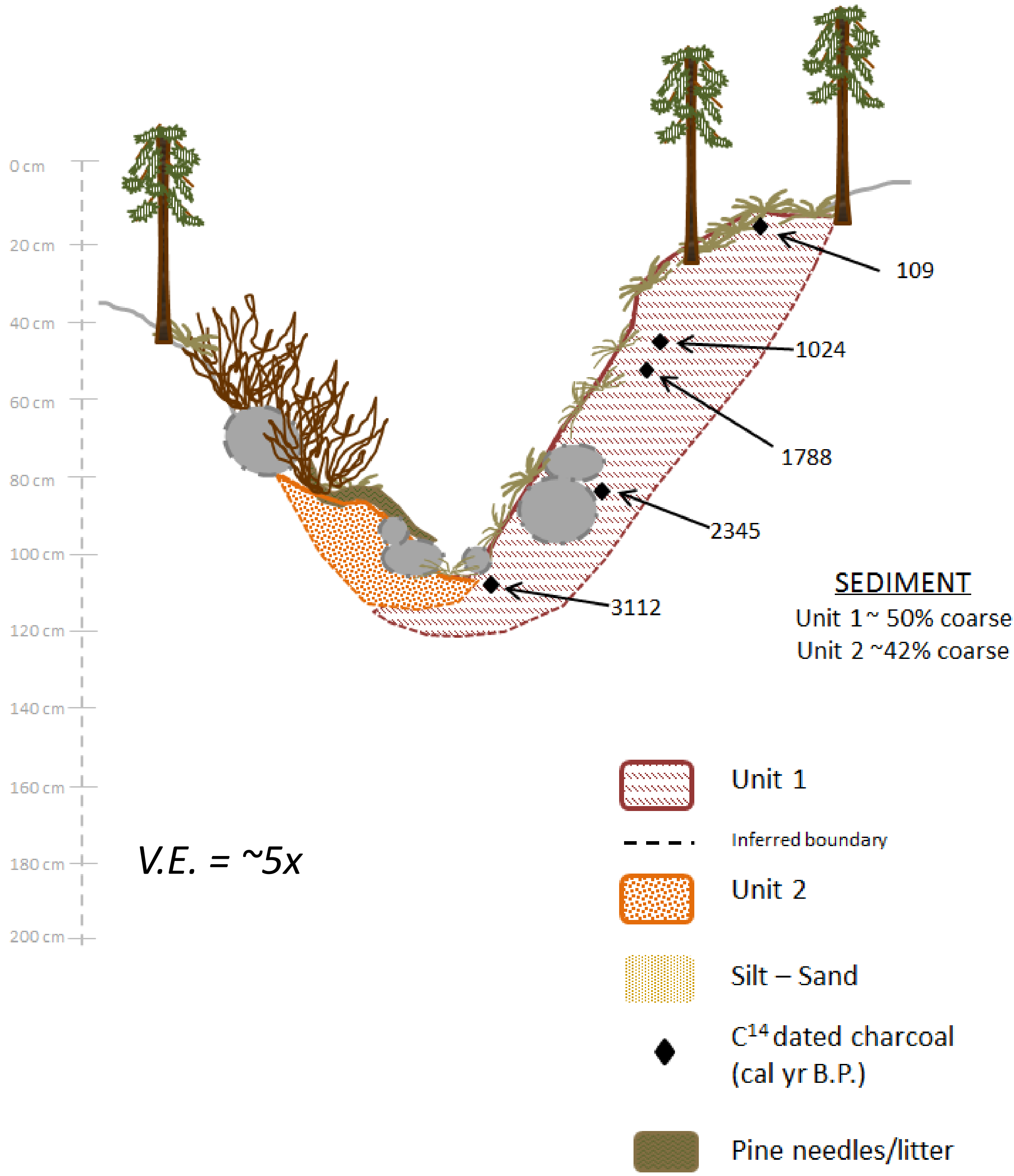


Figure 17. Conceptual diagram of Lower Headwaters subreach of Schultz Creek (see figure 15 for location). % coarse is sediment >2mm diameter.

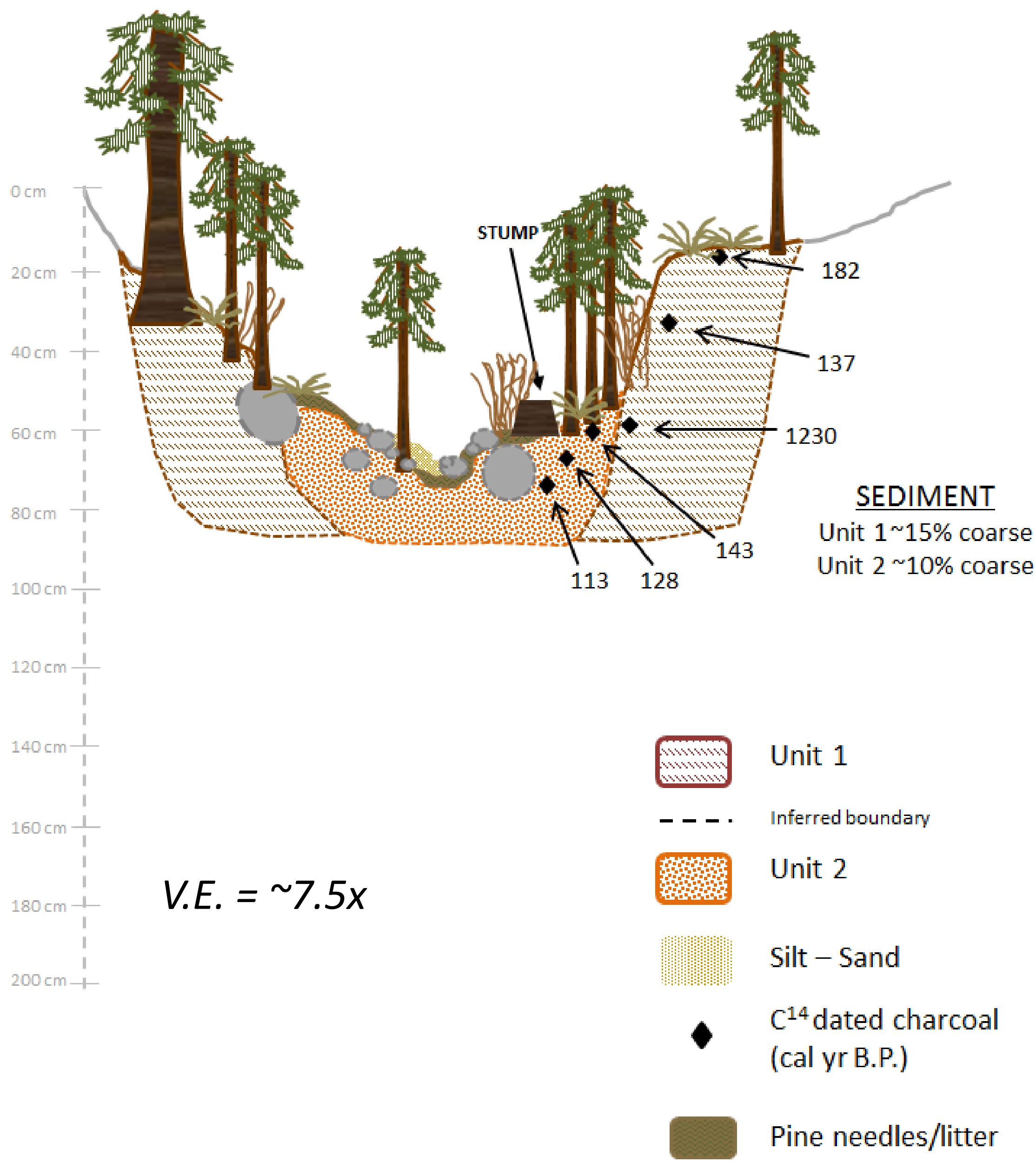


Figure 18. Conceptual diagram of Middle Reach subreach of Schultz Creek (see figure15 for location). % coarse is sediment >2mm diameter.

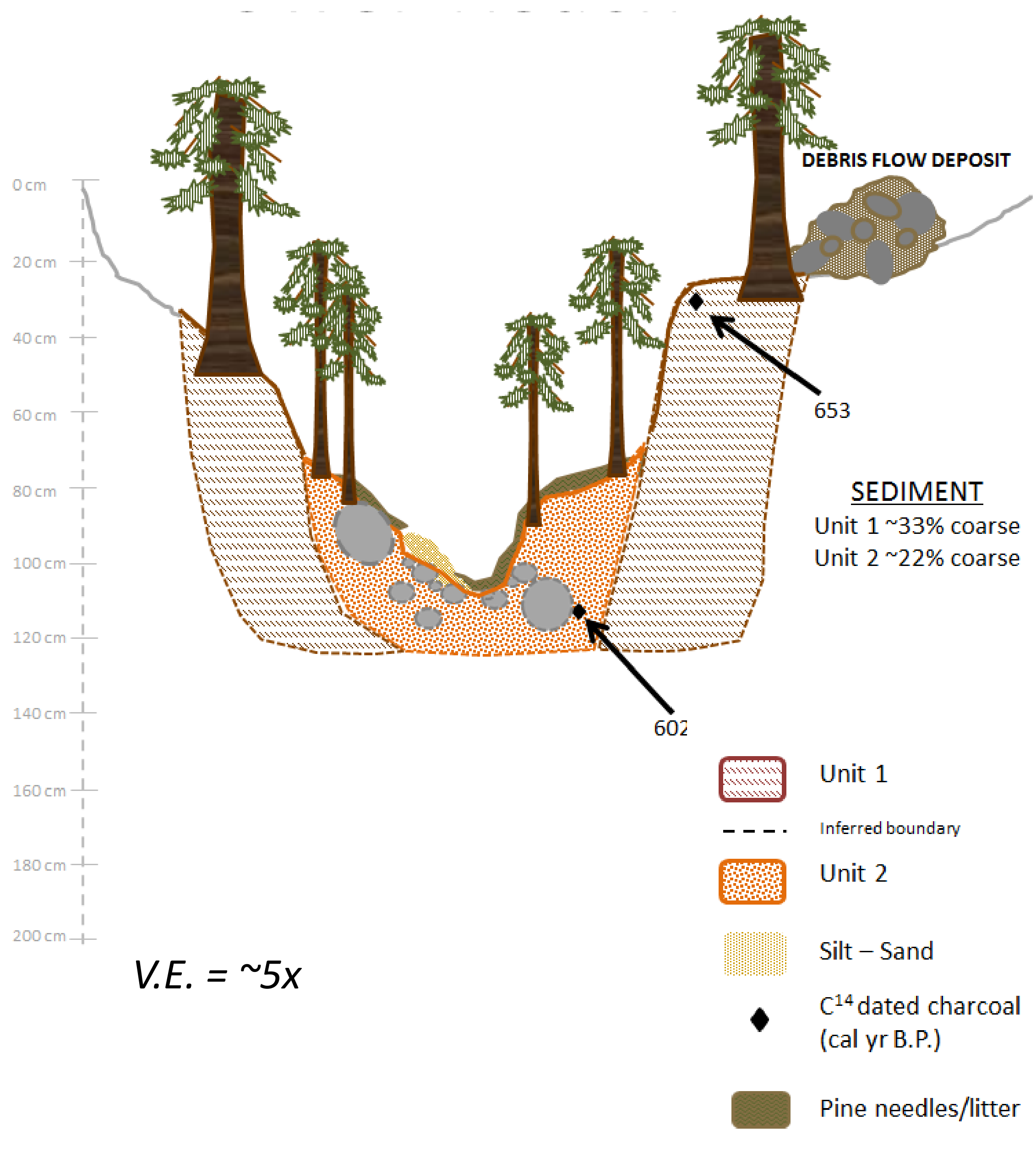


Figure 19. Conceptual diagram of Lower Reach subreach of Schultz Creek (see figure 15 for location). % coarse is sediment >2mm diameter.

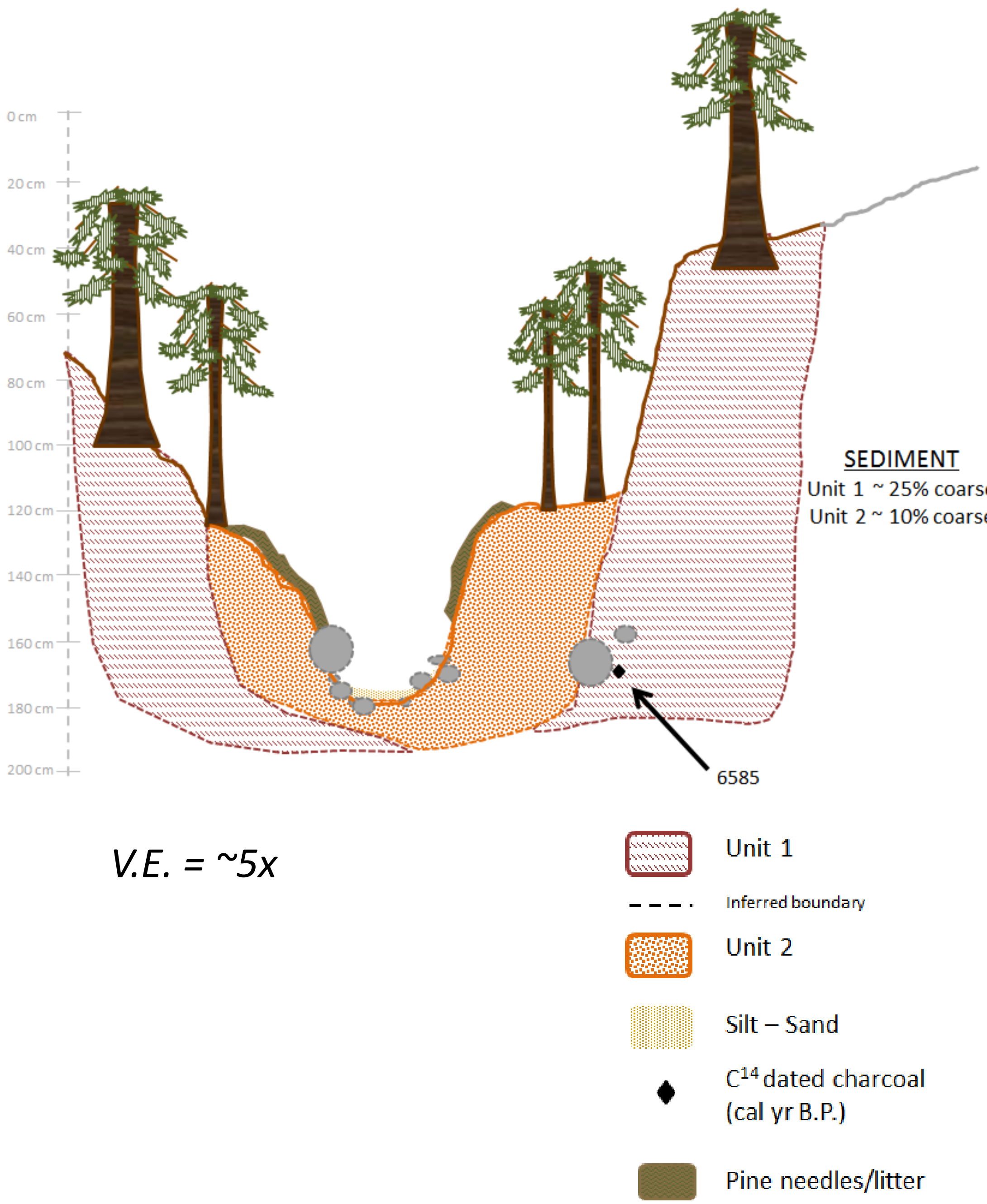


Figure 20. Conceptual diagram of Alluvial Fan subreach Schultz Creek (see figure 15 for location). % coarse is sediment >2mm diameter.

Table 1. Detailed description of Schultz Creek subreaches

SUB-REACH	AVG. CHANNEL SLOPE %	Unit 1 Thickness (cm)	Unit 2 Thickness (cm)	TRENCH/ CROSS SECTIONS	CHANNEL MORPHOLOGY
Upper Headwaters	4.97	140 (CS 18 only)	30 (CS 17 only)	7/ 17 - 18	Above road (CS 18) uniformly entrenched up to 1.5 meters, well preserved terrace. Below road (CS 17) channel only incised 20-40 cm, road construction possible resulted in sedimentation.
Lower Headwaters	4.47	90 (CS 14-15 only)	15-50	6/ 13a - 16	
Middle Reach	3.84	50-95	20 -55	3, 5/ 8a - 12	
Lower Reach	3.03	75-110	30-50	2/ 2 - 7	Slightly sinuous, 0.25 - 0.5 m entrenched.
Alluvial Fan	2.25	100-170	50	1/ 1	Well defined, deeply entrenched up to several meters into coalescing alluvial fans from axial channel and major tributaries.

Table 1. (cont.) Detailed description of the subreaches of Schultz Creek

SUB-REACH	CHANNEL SUBSTRATE	VEGETATION AND LITTER	OTHER FEATURES
Upper Headwaters	Very few medium boulders, no fine grained sediment.	Very grassy, a few ponderosa of diverse size on banks, some needles/litter.	
Lower Headwaters	Lots of small - large boulders in the main channel, less cobbles and pebbles than downstream. Coarse sand behind knick points.	Dense willows in some stretches of channel; grass and herbaceous cover on flood plain and in channel; light covering of needles; less dense trees.	
Middle Reach	Some large boulders, lots of cobbles and coarse sand.	Long, dense grasses and herbaceous cover on channel banks and flood plain; dense woody shrubs; some vegetation in active channel; dense coverage of small ponderosa on banks; in channel; thick coverage of dead pine needles.	26 knickpoints (~17/mile), partially 1/4 m high woody debris and vegetation, partially 1 m high large and medium boulders.

Table 1. (cont.) Detailed description of the subreaches of Schultz Creek

SUB-REACH	CHANNEL SUBSTRATE	VEGETATION AND LITTER	OTHER FEATURES
Lower Reach	High concentration of cobbles and coarse sand, a few large boulders. Small swales of coarse sand from recent flows at some breaks in slope.	Dense ponderosa pine saplings on channel banks and flood plain; thick covering of dead needles, pinecones, sticks on banks, flood plain, and the active channel.	32 knickpoints (21/mile), 1/4 to 1 m high, cobbles to large boulders, woody debris. ~6 relict debris flow deposits parallel to channel containing material ranging from medium cobbles to large boulders, 23-40 m long, 4-12 m wide; numerous small knick points; a few small man-made dams with stones.
Alluvial Fan	Mostly fine grained, sparse gravel, some small cobbles, rare boulders	Dense ground cover of dead needles, pinecones, and sticks, the occasional stump; no herbaceous cover in channel; many large ponderosa pines in channel and on banks.	Knickpoints 1-5 (11/mile), some are man-made, probably from timber harvesting in the early 1900's. natural morphology in some locations; broad, flat flood plain.

Table 2. Soil analysis results of trenches in Schultz Creek

TRENCH	DEPO. UNIT	DEPTH (cm)	MUNSELL (dry)	TEXTURE (<2mm)	% COARSE (>2 mm)	FIELD DESC.	LAB NOTES
7	1	0 - 67	3/2 10 YR	Clay Loam	61	Very clay rich, massive, dark brown, some pebbles, no stratification	
	2a	67 - 102	4/2 10 YR	Clay Loam	33	Dark brown sandy soil, grades into coarse sand with some pebbles (coarsening up)	Charcoal comes out during sieving
	2b		-	-	88	Lenses and strips of densely clustered pebbles up to 1 cm diameter	Not enough sediment for textural analysis
	3	102 -132	4/2 10 YR	Sandy Loam	38	Sandy soil, some pebbles randomly distributed, generally fining up (more pebbles near base)	
6	1	0 - 18	4/2 10 YR	Sandy Loam	51	Organics, dark brown, lots of roots, clumpy soil aggregates, small pebbles	Charcoal and fine roots come out during sieving
	2	18 - 128	4/2 10 YR	Sandy Loam	52	No structure, clay and sand, lots of pebbles and cobbles, large rotten roots	Large pebbles and gravel
	3	128 - 149	4/2 10 YR	Loamy Sand	42	No structure, same texture as U2, lighter brown color, slightly orange	

Table 2. (cont) Soil analysis results of trenches in Schultz Creek

TRENCH	DEPO. UNIT	DEPTH (cm)	MUNSELL (dry)	TEXTURE (<2mm)	% COARSE (>2 mm)	FIELD DESC.	LAB NOTES
5	1	0 - 43	5/3 10 YR	Clay Loam	11	Thin layer of coarser sand at ~13 cm depth, ~4 cm thick. Large boulder at 22 cm depth, more pebbles and gravel in matrix	Unit 2 (U2)
4	1	0 - 23	5/2 10 YR	Loamy Sand	38	Many fine roots, sandy and pebbley, no sed structures	Several small pieces of charcoal come out during sieving
	2a	23 - 38	5/2 10 YR	Loamy Sand	38	Absence of fine roots, more gravel and cobbles than U1, very coarse. Large roots up to 4 cm diameter. Increases in pebble/gravel density with depth, no structure	
	2b	38 - 53	5/2 10 YR	Loamy Sand	47		Large clasts up to 9 cm
	3top	53 - 63	6/2 10 YR	Sand	80	Pebble layer, well sorted	
	3mid	63 - 73		Sand	20	Pebbles grade into very coarse sand	
	3base	73 - 86		Sand	42	Grades into med. coarse sand	

Table 2. (cont) Soil analysis results of trenches in Schultz Creek

TRENCH	DEPO. UNIT	DEPTH (cm)	MUNSELL (dry)	TEXTURE (<2mm)	% COARSE (>2 mm)	FIELD DESC.	LAB NOTES
3	1	0 - 14	4/2 10 YR	Sandy Loam	9	Dark, organics, porous (close to surface). Massive dark brown soil	
	2	14 - 24	4/2 10 YR	Sandy Loam	14	Small black lense, same depth as charcoal sample 3	
	3	24 - 63	4/3 10 YR	Sandy Loam	12	Massive, lighter brown, very rocky, clasts up to 7 cm, moderately indurated	
	4	63 - 78	5/3 10 YR	Sandy Loam	14	Layer of large boulders up to 17cm	
2	1	0 - 59	5/3 2.5 Y	Sandy Loam	30	Lots of roots (2 mm-5mm), massive dark brown soil. Some clasts (pebble - gravel), wetted front ~26 cm deep.	Soil aggregates much less indurated than trench 1
	2	59 - 108	5/2 10 YR	Sandy Loam	36	Less porous than U1, more grey/purple than U1, massive, similar root and clast density as U1	
	3	108 - 125	6/2 10 YR	Sandy Clay Loam	25	Lighte rin color, indurated, clayey, massive. Scarce roots or pebbles	U2
	4	125 - 137	5/2 10 YR	Sandy Clay Loam	20	Greenish band of soil ~4 cm thick. Overall dark brown, massive, clayey, thick soil. Roots and clasts up to large gravel	U2
	5	137 - 157	4/2 10 YR	_ NEED TO DO	19	No change in soil from U4, but contains large boulder ~ 20cm	U2

Table 2. (cont) Soil analysis results of trenches in Schultz Creek

TRENCH	DEPO. UNIT	DEPTH (cm)	MUNSELL (dry)	TEXTURE (<2mm)	% COARSE (>2 mm)	FIELD DESC.	LAB NOTES
1	1	0 - 26	5/3 2.5 Y	Sandy Loam	18	Massive, rounded clasts up to 2cm, rootlets. Possibly depth of wetting front	Soil aggregates very indurated
	2	26 - 68	4/2 10 YR	Clay Loam	40	Massive clay with gravel and pebbles. No sed structure. Max clast size ~3cm, rounded	
	3	68 - 103.5	4/2 10 YR	Sandy Loam	12	Faint sed structure with large, clayey lenses, max thickness ~ 5cm. Less clasts than unit 2 (U2), ~1cm clast size	
	4	103.5 - 133.5	4/3 10 YR	Sandy Loam	11	Faint sed structure - fine sandy-silt laminae	
	5	133.5 - 165.5	5/3 10 YR	Sandy Loam	8	Sandy and massive, large roots (~1.5 cm). Large boulder ~30 cm	

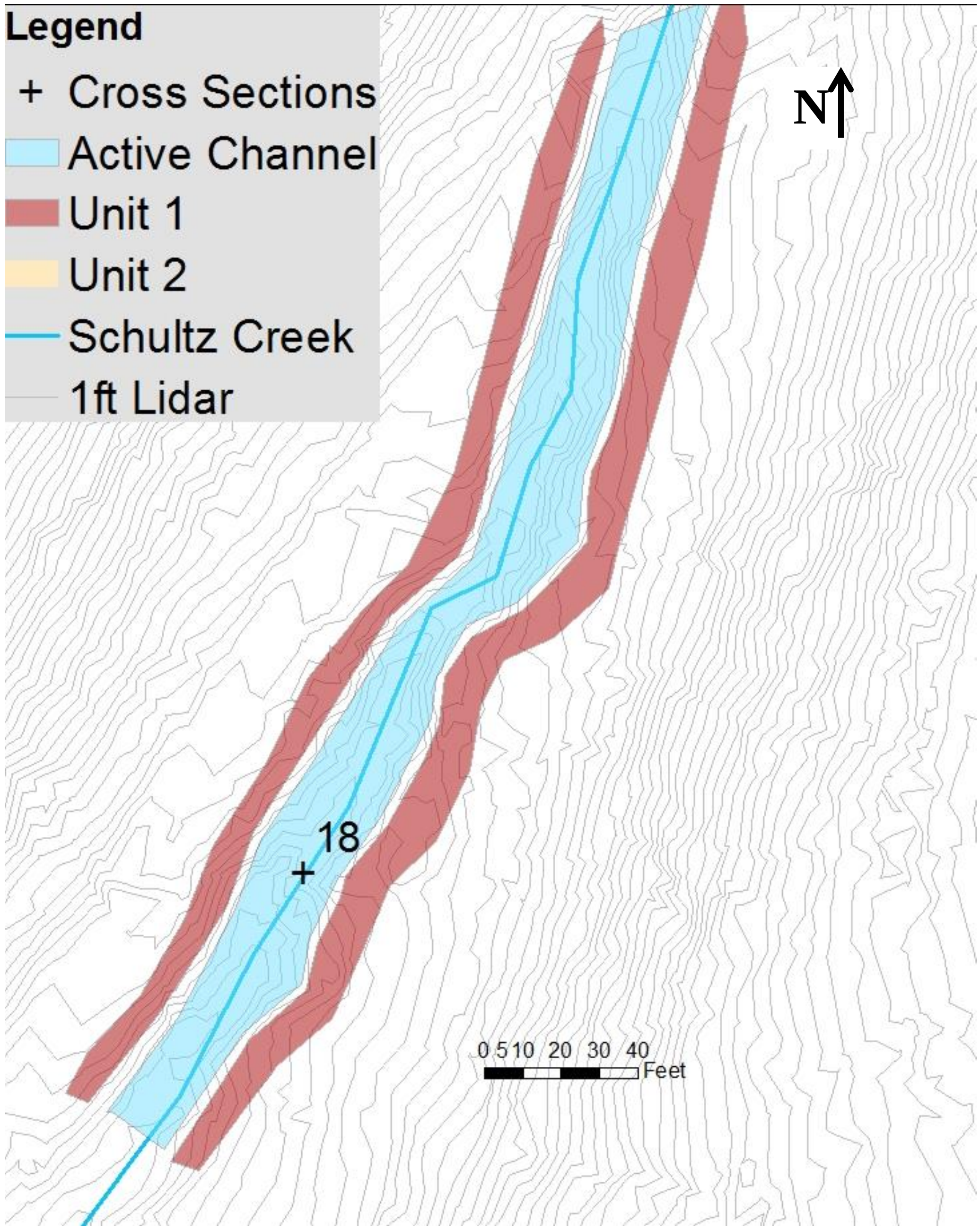


Figure 21. Surficial map of 100 m section of the Upper Headwaters reach. See figure 15 for cross section location.

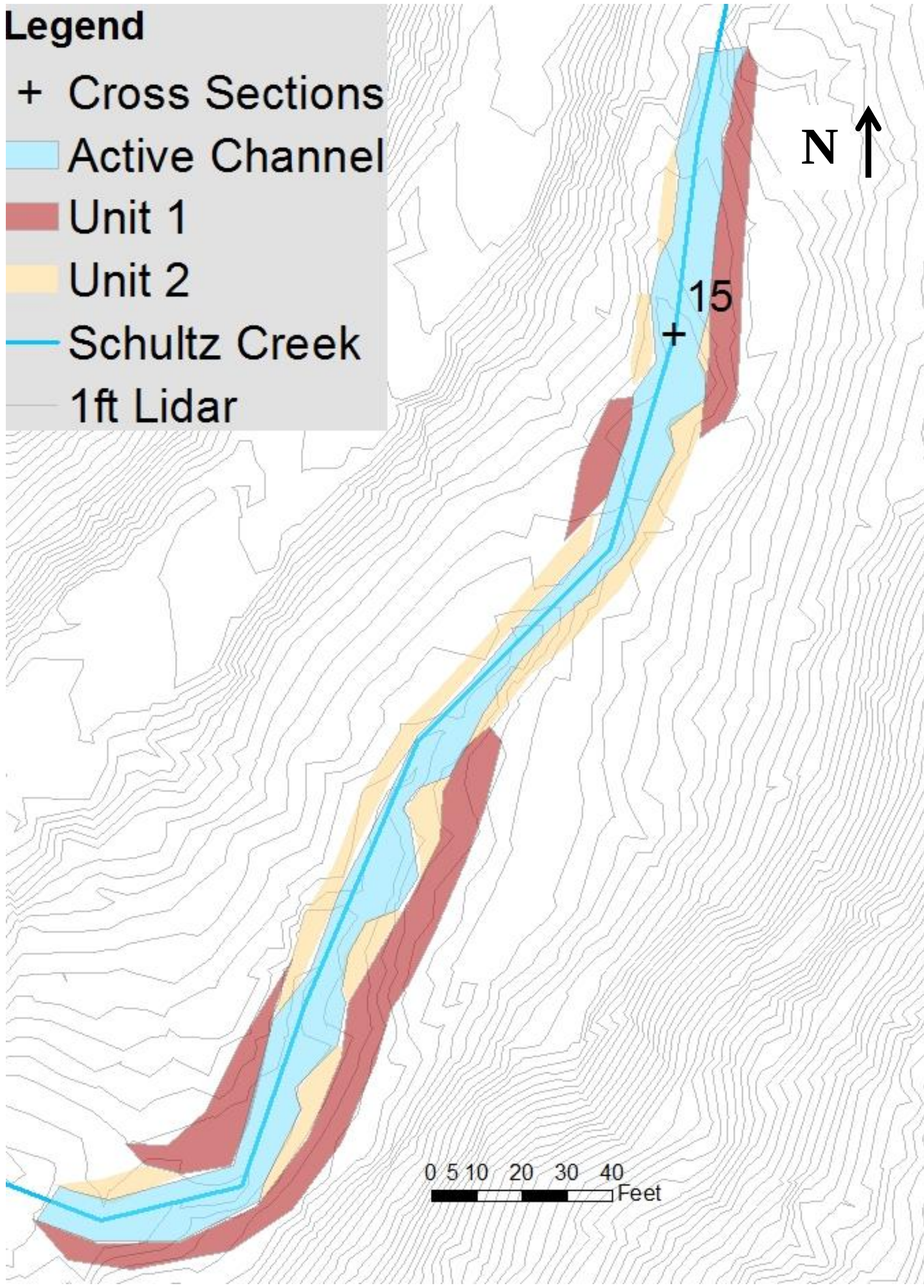


Figure 22. Surficial map of 100 m section of the Lower Headwaters reach. See figure 15 for cross section location.

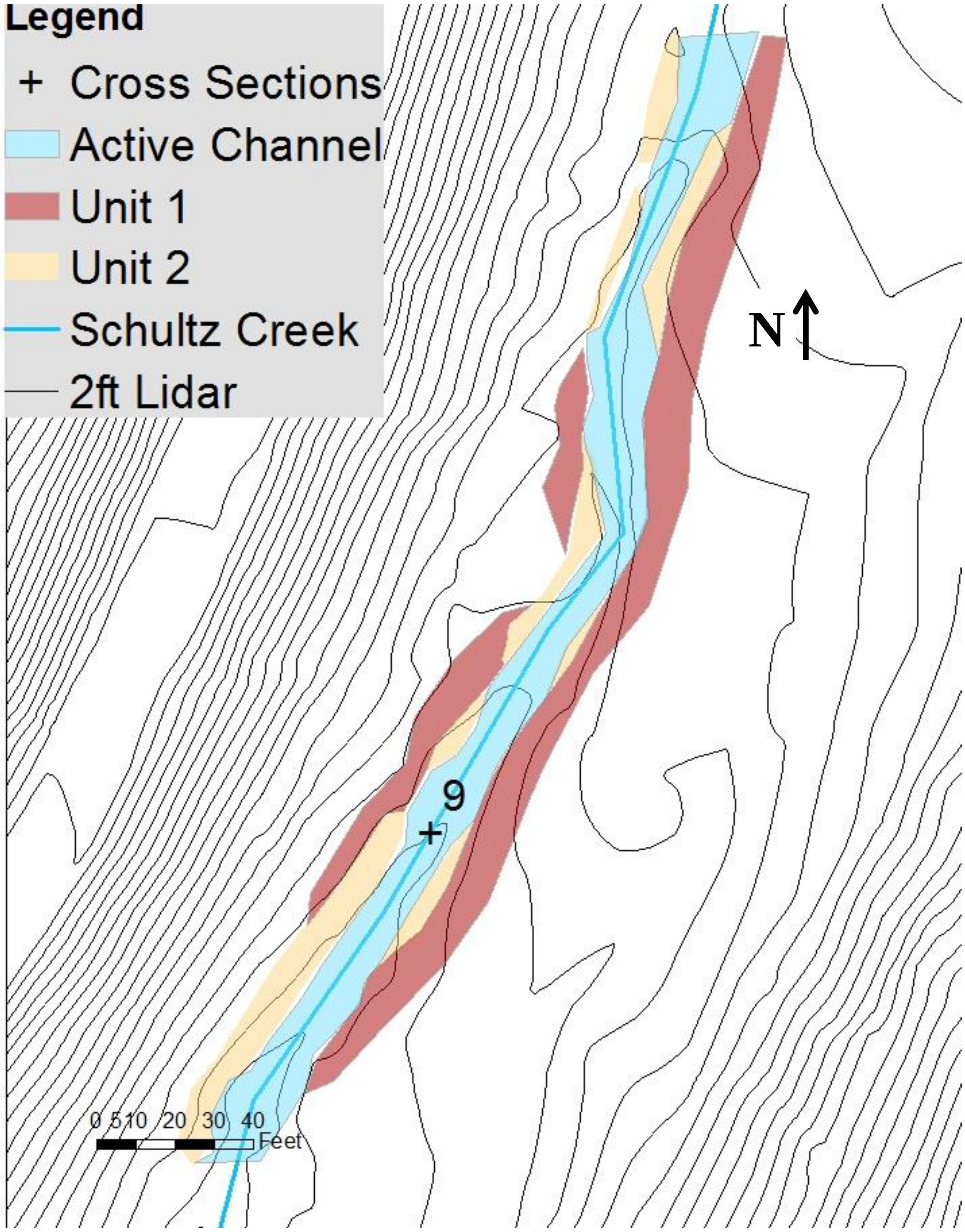


Figure 23. Surficial map of 100 m section of the Middle Reach. See figure 15 for cross section location.

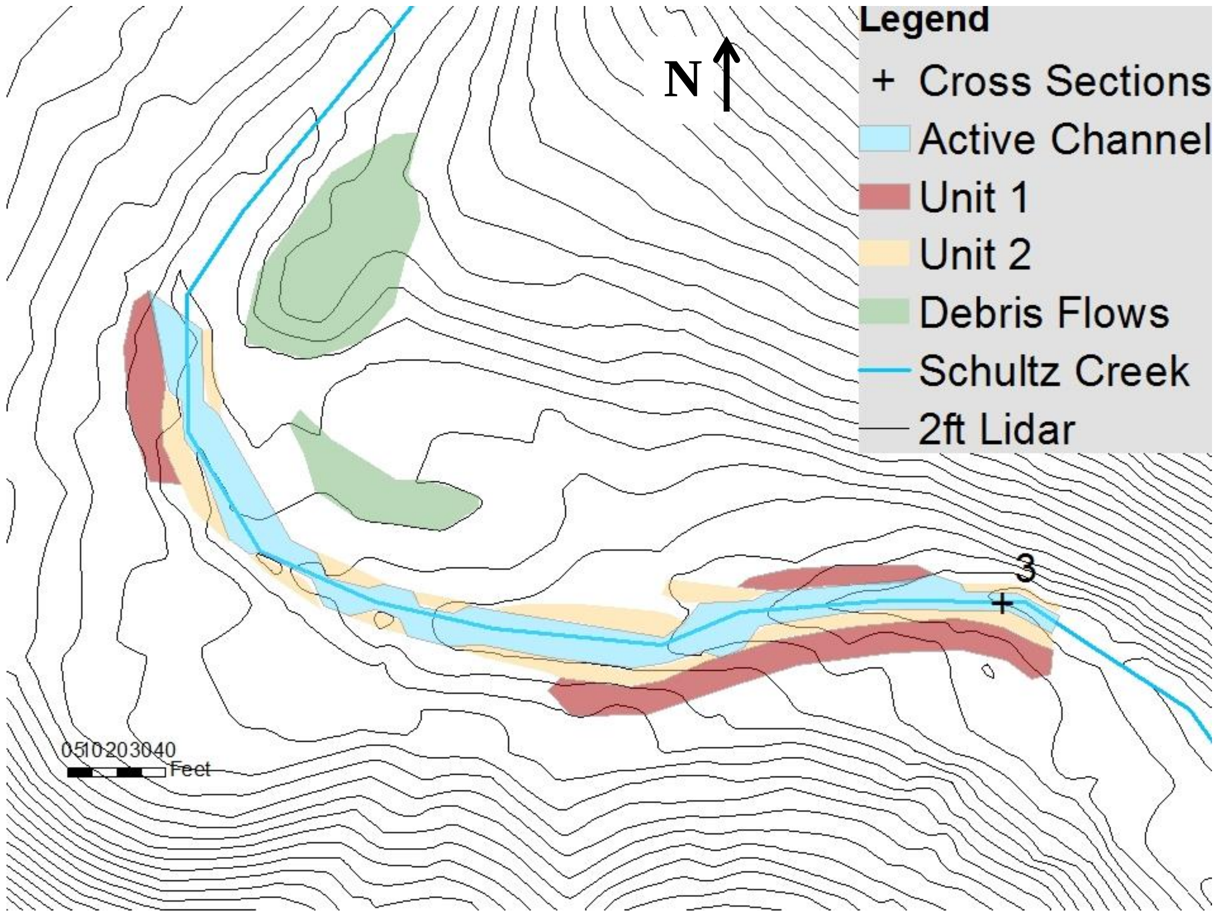


Figure 24. Surficial map of 100 m section of the Lower Reach reach. See figure 15 for cross section location.

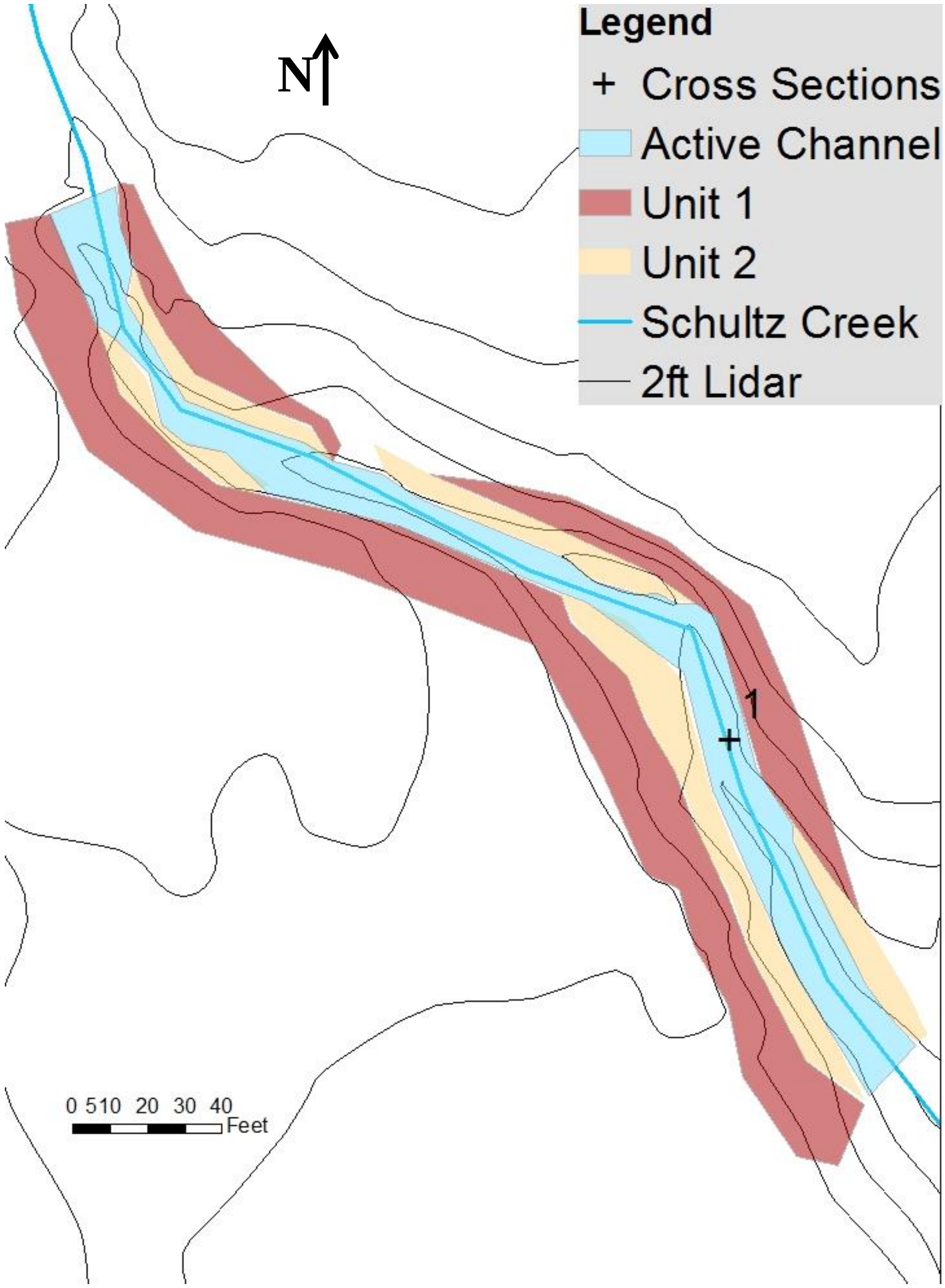


Figure 25. Surficial map of 100 m section of the Alluvial Fan reach. See figure 15 for cross section location.

development. Soil textures of unit 1 are mostly sandy loam and loamy sand, with a few sand lenses. The coarse percentage (>2mm) ranges from 8 to 88%. The soil texture of the top 100 cm of Unit 1 in trench 7 was a slightly finer clay loam with a coarse percentage up to 61%. The unit ranges in thickness from 50 to 170 cm, generally thinner towards the headwaters. Ponderosa pines and other trees of all ages can be found germinating on the terrace surface of Unit 1.

Unit 2 is only intermittently present along the active channel, and can be found adjacent to Unit 1 as well as in places where Unit 1 is absent. Soil textures are slightly finer than those in Unit 1, ranging from sandy clay loam to clay loam. The percentage of coarse particles (>2mm) ranges from 11 to 25%. The unit ranges in thickness from 15 to 50 cm. Only very small diameter trees are found germinating the terrace surface of Unit 2. Medium boulders (17 – 30 cm long axis) were exposed at the base of several trenches (1, 2, 3, 5), just below the active channel level, believed to be relatively correlative all along the main channel. Boulders were found at the level of both Unit 1 and Unit 1.

2.2.1.2 - Debris Flows

The presence of many relict debris flow deposits in and adjacent to the axial channel upstream of the main alluvial fan were noted during reconnaissance for trench site selection (Fig 15; Fig. 26; Fig 27). Charcoal was sampled from five debris flows, one sample per flow.

The debris flow deposits are located on various geomorphic features. Some are directly on or level with the Unit 1 terrace surface, some of which have resulted in the temporary bifurcation of the modern active channel.

2.2.2 - Sediment Analysis

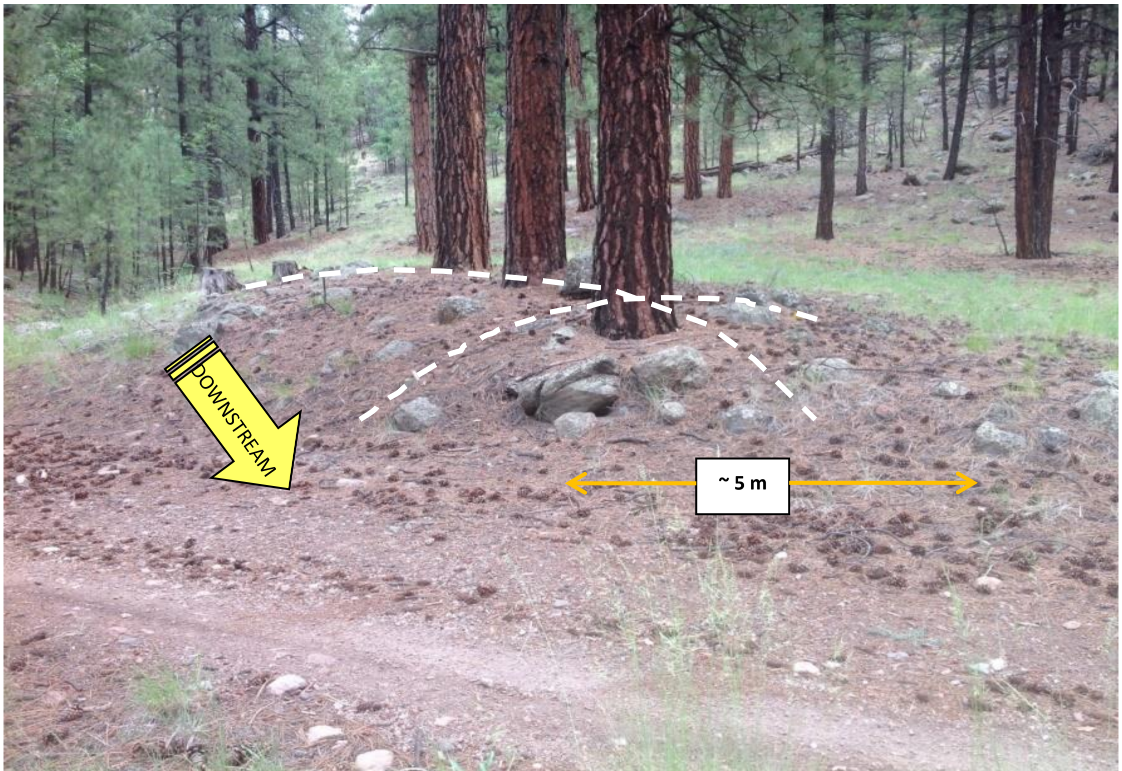
Complete sediment analysis results are recorded in table 2. There was very little variability in sediments of different trenches. The majority of deposits were cumulate, dark brown soil with no structure or stratigraphy. No definitive fire-related deposits were exposed during trenching, which would have been a continuous charcoal-rich or ash horizon in the soil profile. Distinctions between sediment units in profile were made qualitatively in the field based on subtle color differences or shifts in gravel content. Sediment textures were predominately sandy loam/loamy sand, with a few more clay-rich units.

2.2.3 - Longitudinal Profiles

The total-channel longitudinal profile was separated into five smaller longitudinal profiles, one for each subreach of channel (Fig 28). The profiles derived for most reaches of Schultz Creek are slightly concave with a few convex bulges, aka in an erosional phase with knickpoints migrating upstream or a buildup of coarser material (Bull, 1997; Knighton, 1984). The Lower Headwaters reach and the downstream portion of the Middle Reach are slightly more convex, indicating these sections of channel are experiencing more sediment accumulation and are not actively incising at this time.

2.2.4 - Radiocarbon dates

A total of 27 charcoal samples were collected, 22 from trenches along the axial channel and 5 from debris flow deposits, generally within or adjacent to the channel. The first six were submitted to the National Science Foundation-University of Arizona AMS facility. The remaining 21 were taken to the Keck Carbon Cycle AMS Facility, where the author was trained in and assisted with sample preprocessing prior to sample dating. Radiocarbon dating results are in table 3. Trenching in Schultz Creek did not expose any



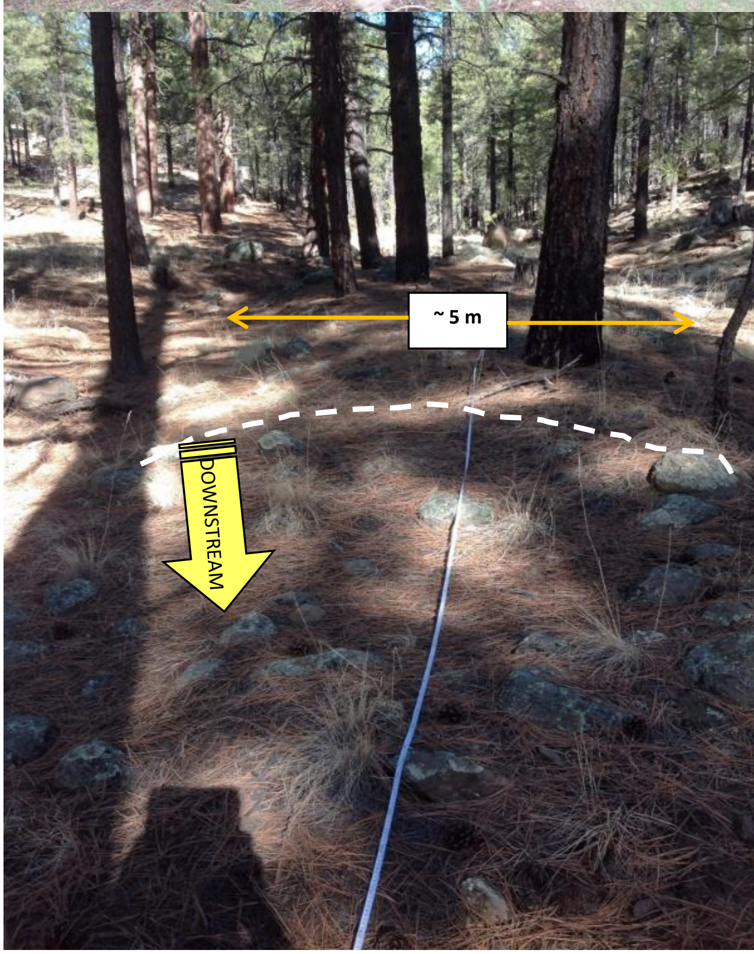


Figure 26 – Debris flow deposits in Schultz Creek. Pictures of debris flow 6 (top) and debris flow 1 (bottom). White dashed lines to emphasize lobe-like, elongate, convex morphology. See figure 27 for debris flow locations.

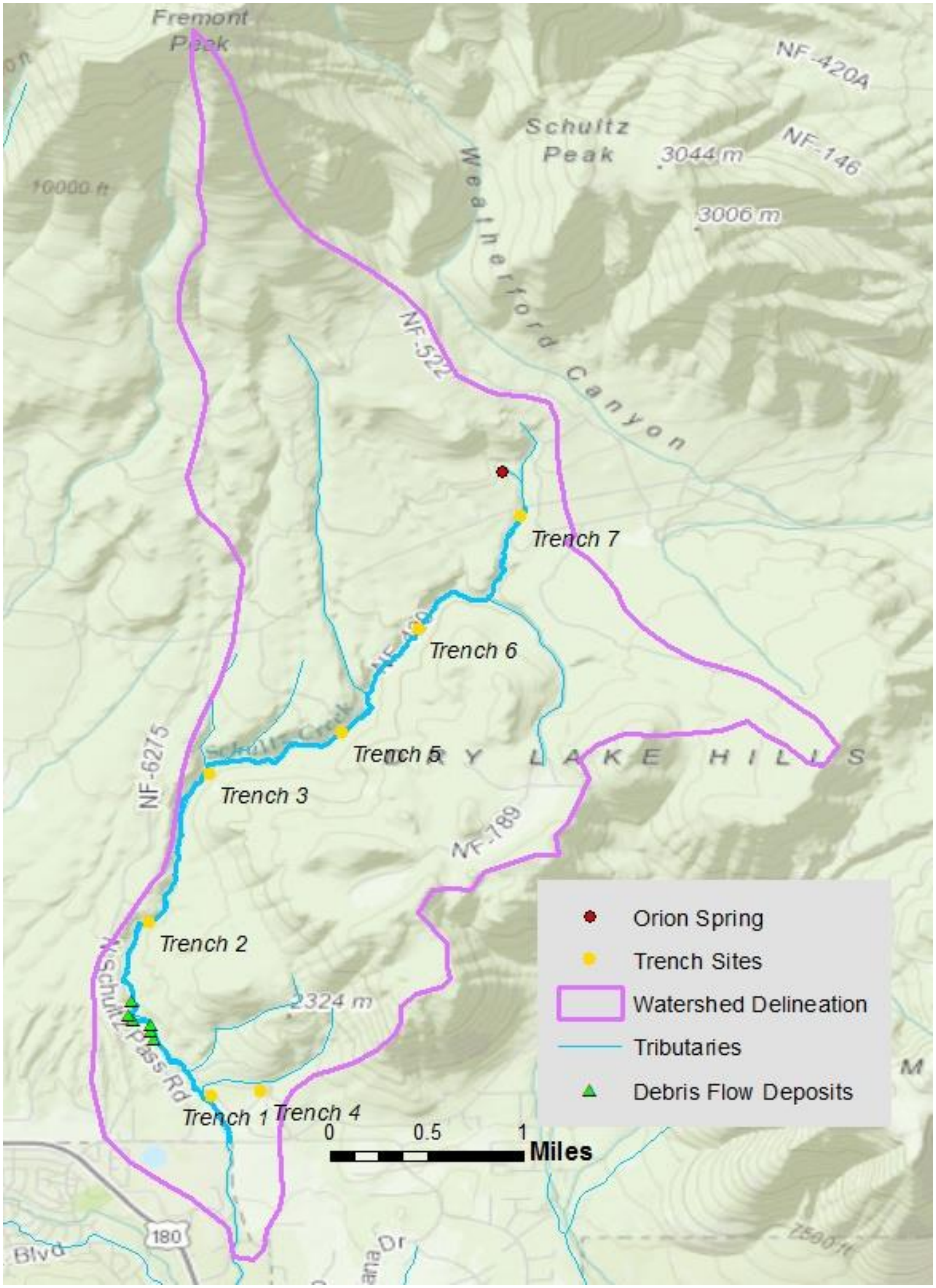


Figure 27 – Map of trench and debris flow deposit locations in the channel.

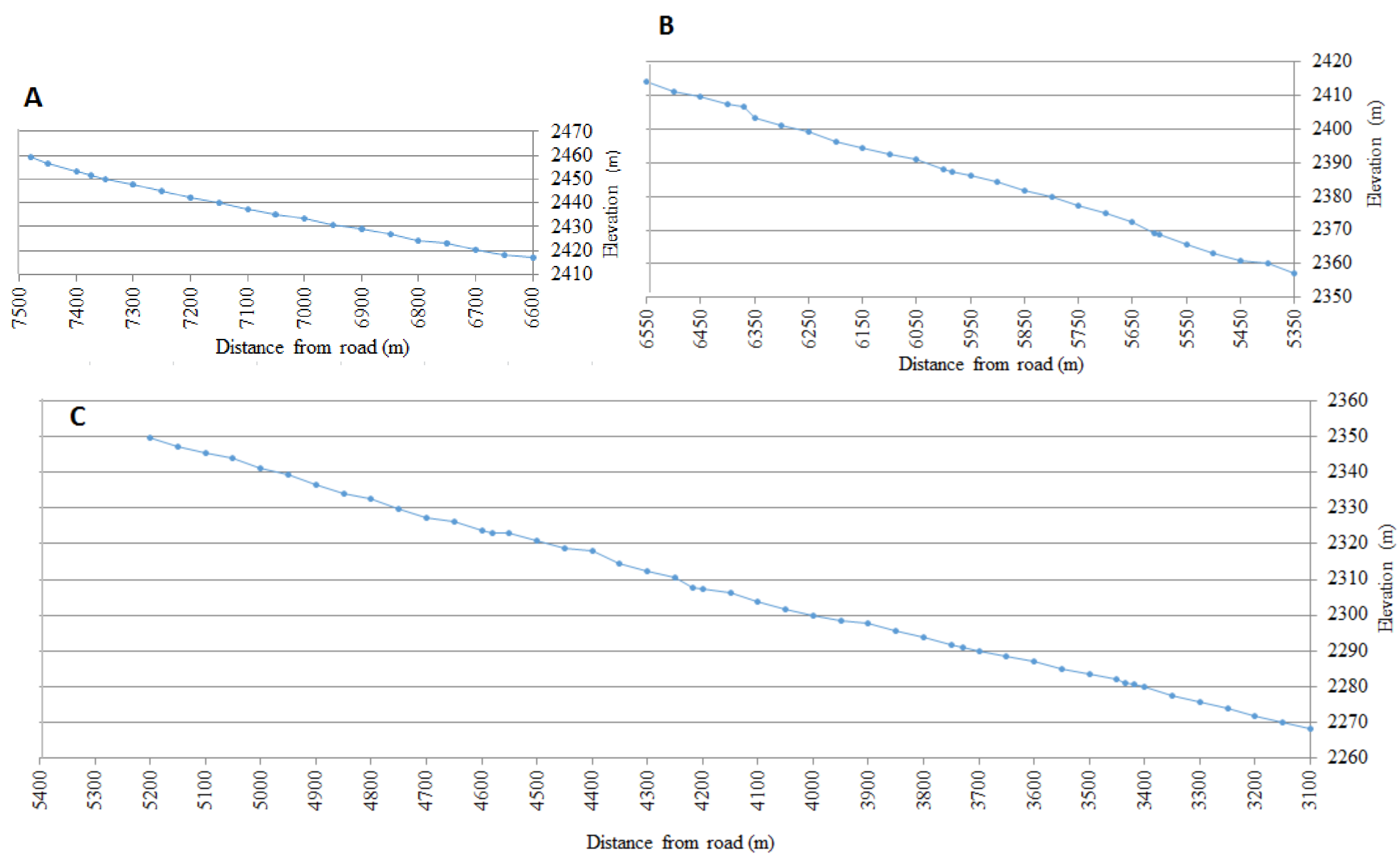


Figure 28. Longitudinal profiles of each reach. A – Upper Headwaters, B – Lower Headwaters, C – Middle Reach.

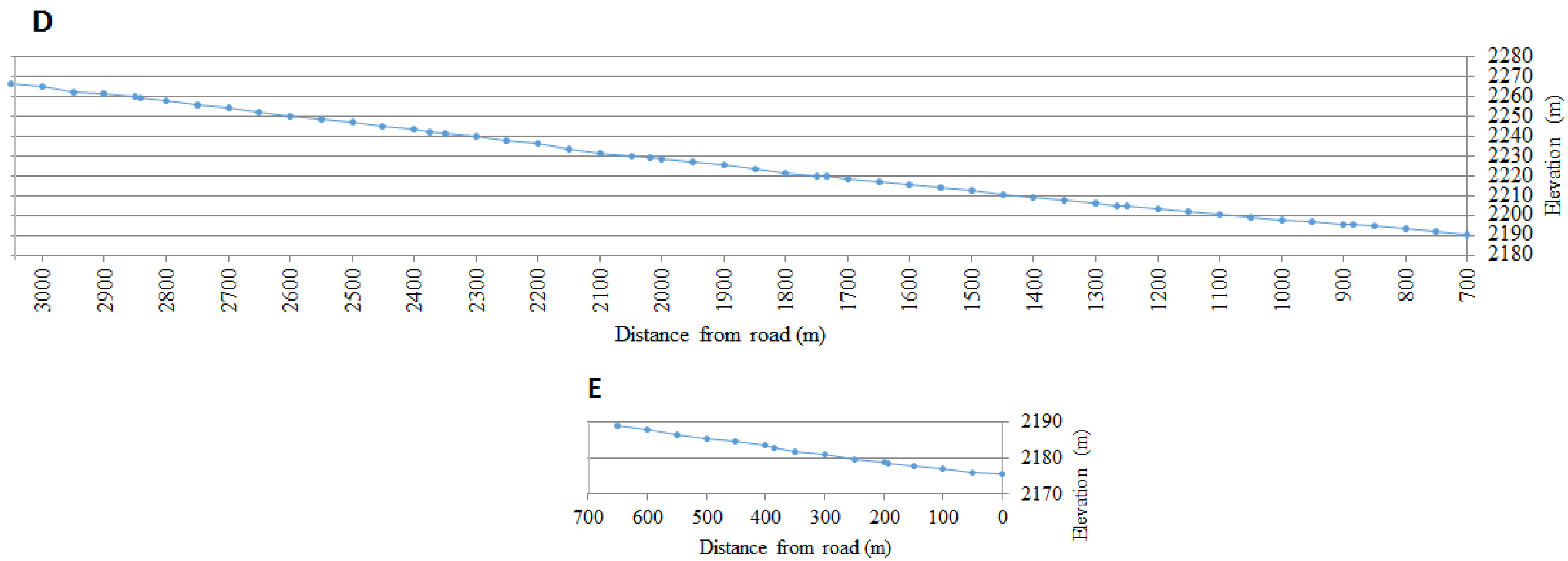


Figure 28 (cont). Longitudinal profiles of each reach. D – Lower Reach, E – Alluvial Fan.

Table 3. Radiocarbon dating results from trenches and debris flow deposits. See figure 15 for trench and debris flow locations.

TRENCH	SAMPLE #	DEPTH (cm)	C^{14} AGE	CALIBRATED C^{14} DATE (yr B.P.)	2σ RANGE
7	1	20.3	2810±15	2910	2866-2954
	2	55.9	3590±20	3891	3838-3966
	3	80	3975±15	4440	4415-4514
	4	108	3705±40	4042	3924-4153
6	1	10.2	120±15	109	21-266
	2	58.4	1100±70	1024	832-1229
	3	71	1855±15	1788	1724-1862
	4	94	2320±15	2345	2331-2353
	5	124.5	2950±20	3112	3007-3174
5	1	17.8	140±15	143	9-275
	4	25.4	135±15	128	11-271
	2	35.6	130±15	113	12-269
4	4	31.8	235±15	291	0-308
	1	40.6	215±20	290	154-304
	2	47.6	250±20	169	0-303
	3	75	240±20	296	0-417
3	3	12.7	204±38	182	0-309
	2	34.3	134±39	137	5-281
	4	53.3	1286±41	1230	1087-1296
2	1	28	693±47	653	554-722
	3	147	597±39	602	538-655
1	1	160.5	5785±50	6585	6453-6716

DEBRIS FLOW	C^{14} AGE	CALIBRATED C^{14} DATE (yr B.P.)	2σ RANGE
5	325±15	384	310-456
4	575±15	608	539-634
3	630±15	593	558-657
2	275±20	313	286-428
1	420±15	499	476-511

fire-related deposits, and all charcoal samples appeared to be wood fragments. Burned twigs and leaves are considered to be the most reliable for determining the timing and location of a fire due to their low residence times on the landscape. Burned wood fragments were likely formed in a fire upstream and later reworked and transported fluvially, possibly several times, and ultimately deposited in their present locations. Soil units with a noticeably higher density of charcoal fragments were noted during trenching, but the lack of fire-related deposits or flood deposits makes charcoal density information less germane. Fire-return intervals cannot be inferred from the radiocarbon results in this study. The ages of charcoal samples indicate a maximum age of deposits, i.e. sediments overlying a charcoal fragment have been aggrading for less than the age of that fragment. The radiocarbon dates provide age constraints for geomorphic units and were used to develop an alluvial chronology for this watershed, discussed in detail in section 2.3.

2.2.5 - Sediment Volume

Aerial LiDAR is available for cross sections 1 – 9 from the City of Flagstaff (2 ft contour intervals) and for cross sections 12 – 18 from Coconino County (1 ft contour intervals). Valley wall slopes for cross sections 10 and 11 were measured manually using a Topcon Laser Level and stadia rod. Control points with exact elevations were established as close as possible to cross sections 10 and 11 using a GNSS CS25 GPS unit. The estimated relative precision of the vertical control established with the GNSS is approximately 4-8cm. The 250 m channel length interval for measuring cross sections fell on a knick point in two locations, cross section 8 and cross section 13, warranting two cross sections at these locations, one upstream and one downstream of the knickpoint. GNSS control points have a +/- 1 cm horizontally, +/- 2-3 cm vertical accuracy when the

RTN is available, and about twice that when RTN not available. The GIS Pro app on the Ipad 4 has an error of up to several feet. The sediment volume results are in table 4. A total of 885,107 m^3 (31,257,276 ft^3) sediment is estimated to be stored in the channel, with an average of 1,465 ft^3 per foot of channel. Using the sediment bulk density of 1.57 g/cm^3, sediment volume was converted to a total mass of 1,531,791 tons for the entire channel (62 tons/ft channel). This is equivalent to about 520 football fields.

Table 4. Volumes of sediment per reach of Schultz Creek. Locations of reaches shown on figure 15.

Cross section	Reach Length (ft)	Reach Sediment Volume (ft^3)	Subreach	Sediment Volume (ft^3) per ft Channel Length
1	2418	9345570	Alluvial Fan	3865
2	1052	2767286	Lower Reach	1293
3	1478	529231		
4	1144	2871440		
5	1136	766598		
6	1296	1769313		
7	1728	1425600	Middle Reach	1028
8a	1405	1545830		
9	1297	2453167		
10	1419	862164		
11	1111	813252		
12	1060	686880		
13a	1205	1624340	Lower Headwaters	914
14	1229	1793610		
15	1358	929146		
16	1744	493552		
17	1757	54458	Upper Headwaters	223
18	840	525840		
total sed volume:		31257276	Average:	1465

2.2.6 - Rate of Deposition

A rate of deposition was calculated for trench 6 (samples 1-3) and 7 (samples 1-5). This suite of samples were selected because of their accurate chronological order with the oldest at depth, as well as the wide spread of ages for both trenches; trench 6 charcoal ages range from 3112 yr B.P. to 109 yr B.P.; trench 7 charcoal ages range from 4440 yr B.P. to 2910 yr B.P.

There was some variability of deposition rates for different age intervals in trench 6: 0.398 mm/yr (3.98 cm/1000 yr) from 3112 to 2345 yr B.P, 0.413 mm/yr (4.13 cm/1000 yr) from 2345 to 1788 yr B.P., 0.165 mm/yr (1.65 cm/1000 yr) from 1788 to 1024 yr B.P., and 0.527 mm/yr (5.27 cm/1000 yr) from 1024 to 109 yr B.P. The average rate of deposition is 0.430 mm/year (4.30 cm/1000 yr) for trench 6 and 0.394 mm/year (3.94 cm/1000 yr) for trench 7.

2.3 - DISCUSSION

2.3.1 – Alluvial Chronology

Local climate during the late Holocene was variable and in flux according to a bristlecone pine dendrochronology study in the San Francisco Peaks (Salzer, 2000) (Figure 29). In the 1,419 year bristlecone pine record, 42 extreme intervals were identified when both climate and precipitation varied significantly from mean conditions. Seventy-two% of the local extreme dry periods and 48% of the local extreme wet periods overlap with similar precipitation extremes for west-central New Mexico, suggesting that these were regional episodes rather than local. The San Francisco Peaks climate showed both local and regional scale variations during this period of record.

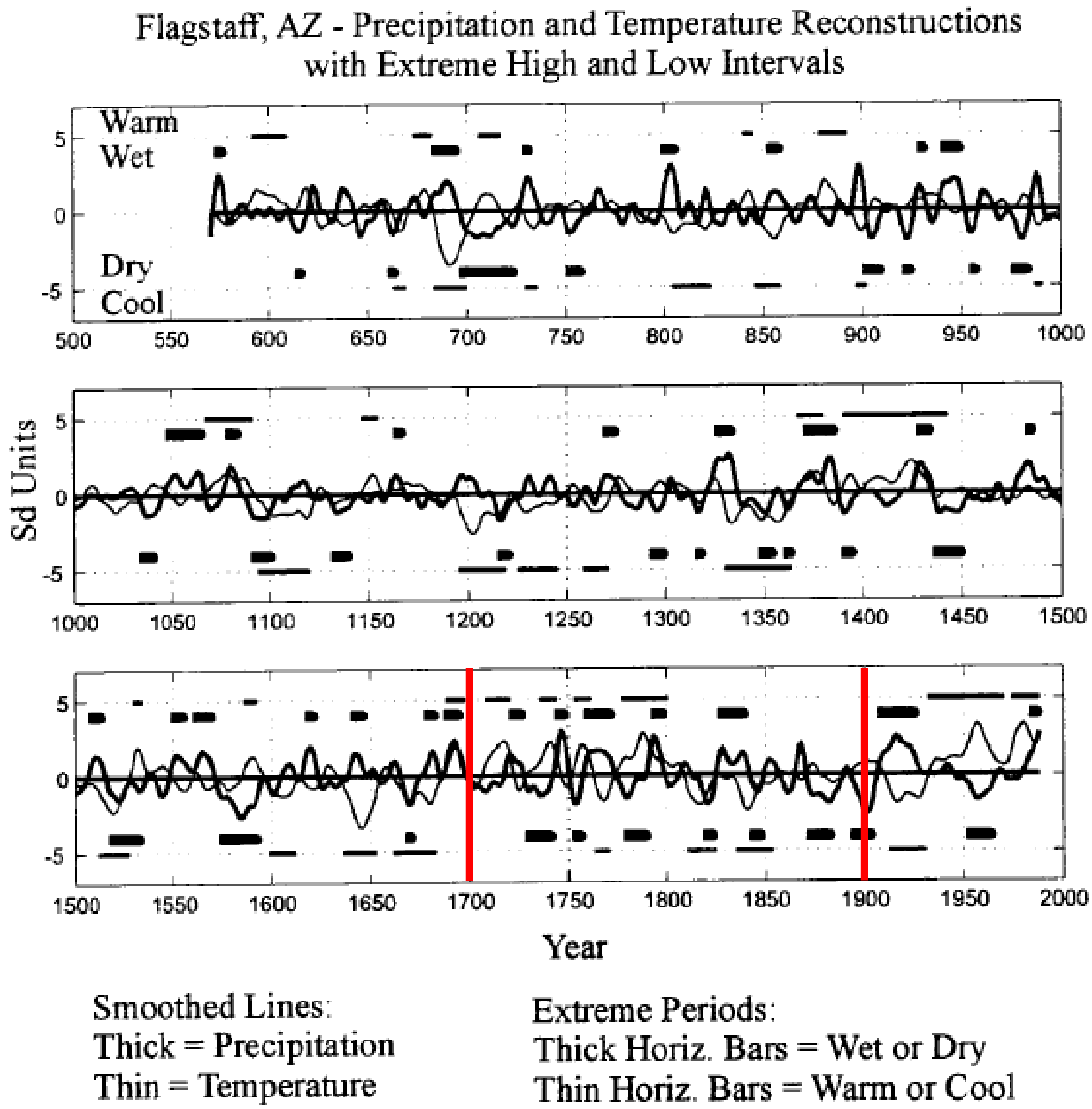


Figure 29. Flagstaff climate record from a dendrochronology study in the San Francisco Peaks (Salzer, 2000). Red bars represent two most recent alluvial chronology thresholds, summarized in table 5.

Local and regional climate studies were used to interpret the depositional history of the Schultz Creek watershed with age constraints provided by charcoal radiocarbon ages. There are a few major thresholds and events evidenced by the geomorphology and sediment records of this watershed: (1) the period of aggradation for Unit 1; (2) initiation of the series of debris flows deposited in the Lower Reach; (3) incision of Unit 1; (4) deposition of Unit 2.

Unit 1 represents a long, relatively consistent period of aggradation along the main channel. This is supported by the thickness of the unit, the (non-stratigraphic inversion) of charcoal ages, its consistent presence along a majority of the main channel, and lack of bedding or stratigraphy. The sediments resemble deposits at a site on the Mogollon rim studied by Joyal (2004) – dark brown, unstratified, cumulic soil, believed to be deposited prior to 1970± yr B.P. during a regionally recorded period of steady aggradation. The oldest charcoal fragment taken from Unit 1 is 6585 cal yr B.P. (year 4572 BC) (Figure 2.7.5). This correlates to the end of a major incisional event evidenced in sediment records across the northern Arizona region that occurred sometime prior to 6000 yr B.P (Joyal, 2004; Anderson et al., 2003; Neff et al., 2003). In Walnut Canyon (~2015 m), about 21km away from the base of the San Francisco Peaks (2,134 – 3,851 m), the incisional period ended earlier, around 8000 yr B.P. (Neff et al., 2003). The regional period of aggradation began later at sites closer to the Mogollon Rim, aka at lower elevations (Joyal, 2004; Anderson et al., 2003).

This was around the transition to the mid-Holocene thermal maximum. Paleoclimate records from northern Arizona in places such as Potato Lake (2222 m elevation) (Anderson, 1993) and Stoneman Lake (2050 m) (Hasbargen, 1994) evidence very warm and dry conditions from approximately 8000 to 4000 yr B.P. The records at Walker Lake (2700 m) has a record of the lowest water record in 20,000 years at about 6000 yr B.P., probably the peak of the dry period in the San Francisco Peaks region (Hevly, 1985). The dry period probably allowed sediments to aggrade because more sediments could be stored on hillslopes without being immediately eroded and washed out of watershed as they were during the preceding wet period when erosion was the predominant process.

The warm and dry conditions of the mid-Holocene were interrupted sometime around 2000 yr BP (Hevly, 1985), and the late-Holocene was generally cool and wet (Weng and Jackson, 1999). Modern analogues indicate that cool and wet conditions in this region result in high runoff and erosion (Salzer, 2000), although there is no clear evidence of erosion in Schultz Creek until the late 1800's.

The radiocarbon dates for the charcoal sampled from debris flow deposits in the lower reach range from 313 to 608 cal yr B.P. (Table 3). The dates from the debris flow deposits do not provide insight into the precise timing of deposition, other than the fact that each debris flow must post-date the formation of charcoal from its deposit. The top of the debris flows are higher in elevation than Unit 1. It is unclear where the bases of the debris flows are, but Unit 2 seems to have been deposited around the debris flows. It is possible that there were several low-magnitude fires in the uplands of the Schultz Creek watershed between 300 and 600 cal yr B.P., and the debris flows occurred sometime after 313 yr B.P. (year 1700) when the climatic conditions were suitable. Hereford (2002) has identified a period from A.D. 1400 to 1880, correlative with the Little Ice Age (LIA), during which valley-fill alluvium deposition was widespread across the southern Colorado Plateau. Regionally, climatic conditions were relatively cool and dry. This period of region-wide alluviation is attributed to a long-term decrease in high magnitude floods. In other words, before and after the LIA, high-magnitude flooding was much more frequent and alluviation was not always possible due to erosive flooding. The debris flows could have resulted from over-saturated soils, only possible with low-magnitude high-frequency precipitation that would have occurred during this period.

There are many possible causes of debris flow initiation including rainfall. Primary climatic factors such as intense rainfall or snowmelt can directly trigger debris flows. These events can lead to rapid infiltration causing soil saturation and temporary increase in soil pore pressure, potentially causing debris flows or landslides. Secondary climatic factors can also influence debris flow initiation such as antecedent rainfall or snowmelt which can increase potential for debris flow initiation during intense rain (Wieczorek and Glade, 2005).

Local climate studies point to high climatic variability during the LIA period (Salzer, 2000), but there is consensus between local and regional climate and sediment studies that high magnitude flooding was common at the end of the 1800's until the late 1930s (Hereford, 2002).

The youngest charcoal fragment extracted from Unit 1 is 109 yr B.P. (year 1904) (Figure 17). There is no evidence in this dataset to suggest that the period of aggradation during deposition of Unit 1was dramatically slowed or interrupted prior to 109 yr B.P. The shift from an aggradational to an erosional system probably began sometime around or after 109 yr B.P. in the Schultz Creek watershed. This date corresponds to an increase in effective precipitation from A.D. 1907-1926 following drier conditions that had persisted for 33 years (Salzer, 2000), an increase in the frequency of large floods (Hereford, 2002), and subsequent erosion across northern Arizona (Hereford, 1984). Climate did play a role in the high-magnitude incision at the turn of the 19th century, but this was also due in part to anthropogenic forcing. Thousands of cattle were introduced to the region in 1875, and were overstocked by 1880 (Masek Lopez and Springer, 2002). Overgrazing and drought in the mid-1890's significantly reduced vegetative cover, resulting in increased runoff and erosion and severe downcutting of streams (Hereford 1984). Unit 2 is less clearly defined than Unit 1 and is less consistently present along the main channel. The charcoal ages in Unit 2 do not exceed 602 cal yr B.P. and are mostly younger than the oldest charcoal ages preserved in the top of adjacent Unit 1 deposits (Figure 18, 19).

Unit 2 probably consists of sediment reworked from the top of Unit 1 and deposited in the active channel after the period of dramatic incision of Unit 1 ceased. Unit 2 sediments were probably not transported far downstream from their source locations on the terrace surface of Unit 1reflects erosional responses to more local climatic forcing. Incision of Unit 1 and deposition/reworking of Unit 2 is still actively occurring at the present (Summary of alluvial chronology in table 5).

2.3.2 - Sediment Volume

Previous sediment yield simulations were compared to the simulations developed with this study. The Forest Service simulated the mass of annual hillslope sediment delivery (tons). After a wildfire in Schultz Creek watershed with no wildfire, 14,912 tons of hillslope sediment yields are estimated in the first year post-fire, according to the ERMiT modeling performed by the Forest Service (Runyon, 2014). Synthesis of post-fire sediment yield literature has revealed that approximately 25% of post-fire sediment is sourced from hillslopes, and the remaining 75% from channels. If we assume that 14,912 tons is only 25% of the total potential sediment yield, the approximate total sediment yield would be 59,648 tons, with 44,736 tons being sourced to the channel. Total stored sediment in the Schultz Creek channel is estimated to be 1,531,791 tons. Total stored sediment would not necessarily be mobilized; this mass reflects what is *available* for transport. 44,736 tons is only about 1% of the estimated total sediment stored in the channel. There are several possible explanations for the disparity between the stored channel sediments and the Forest Service hillslope sediment modeling. It is possible that the hillslope sediment yields are underestimates due to modeling assumptions, or the sediment volume estimates in this study are overestimates due to overestimates of bedrock depth. The soil bulk density value (1.57 g/cm^3) used for the sediment in Schultz Creek could be an overestimate, although the low end of soil bulk density values for sandy loams is about 1.40 g/cm^3. When using 1.40 g/cm^3 as the soil bulk density, the mass of stored channel sediments is still the same order of magnitude (~1.3 million tons), so the mass of sediment is not very sensitive to soil bulk density. There is a lot of coarse material in the channel sediments ranging from cobbles to boulders, but solid rocks have a bulk density of 2.65 g/cm^3 (Arshad et al., 1996), so taking this into account would only increase the mass of stored channel sediments.

The appropriateness of the bedrock cross sectional morphology and the resulting stored sediment volume is likely in the correct range, but could be improved with a more exhaustive literature review or collection of additional field data, such as geophysical surveys of the sediment thickness stored in channels. The assumption of a “V” shaped

Table 5 – Alluvial chronology summary for Schultz Creek based on radiocarbon dating of charcoal and soil analyses

Event	Occurrence (cal yr B.P.)	Climate	Possible Cause
Beginning of Unit 1 deposition	~7,000	Transition from wet/cool to very warm and dry	End of region-wide period of erosion, climatic forcing
Debris flows	~300	Cool and dry conditions during the Little Ice Age from 1400 to 1880 AD	Widespread alluvial aggradation across the southern Colorado Plateau due to long-term decrease in high magnitude floods. Increase in low-magnitude floods increased potential for debris flows.
Incision of Unit 1 and deposition of Unit 2	~109 - present	Dry period (A.D. 1871-1904) followed by wet period (A.D. 1907-1926).	Climatic sequencing and European land use practices such as grazing livestock and timber harvesting.

bedrock channel was used to simplify the channel geometry to make a stored sediment volume estimate. If the bedrock channel is actually a “U” shape, the volume estimate resulting from this study could be under or overestimates depending on the depth of the bedrock erosion. A limited literature review indicated some models for determining rates of bedrock erosion, although there does not seem to be any specific law about the shape a bedrock channel will erode into. According to the models, it depends on numerous factors such as climate, the channel slope, the geology, discharge, average grain size and bedload sediment supply, drainage area, and vegetation (Montgomery and Buffington, 1997; Seidl and Dietrich, 1992; Finnegan et al., 2005; Wobus et al., 2006). Although it is out of the scope of this project, one of the erosion models could be used to simulate erosion of bedrock in conditions that could have caused bedrock erosion in the study area to improve sediment volume estimates. As an alternative to modeling, observation of bedrock morphology of a channel denuded of sediment with similar climate, slope, and geology as the study area would improve estimates of sediment volume. Probing to depth of the bedrock in the study area or implementation of shallow geophysical techniques could also help improve the sediment volume estimate.

Major erosion after the Schultz Fire in July 2010 resulted in scouring down to bedrock at some locations of the channel, with maximum scour depth about 4 meters deep. My inferred bedrock depth beneath stored channel sediments ranges from 1.4 to 8.8 m, with mean of 4.9 m, so the sediment volume estimation method used in this study is feasible. It is unlikely that all sediment stored in the channel would be mobilized in one runoff event, or even over the course of one monsoon season, post-burn. After the first monsoon season post-Schultz Fire, it was estimated that 15,000 m^3 of sediment had been recently disturbed and was unstable but had not yet exited the channel network (Carroll, 2011). There were also large volumes of sediment stored directly adjacent to the main channel (in channel banks) that were predicted to be mobilized in future high runoff events, but generally remained in place following the monsoons of 2010. The estimated volume of stored sediments for Schultz Creek in this study includes active channel sediments and channel bank sediments, therefor it is not an estimate of sediment that necessarily would or could be mobilized in a single post-burn runoff event, simply a volume of unconsolidated sediments stored in and directly adjacent to the main channel. The estimate of total stored sediment in Schultz Creek is equal to approximately to 884,600 m^3. 15,000 m^3 is only about 1.7% the estimated stored sediment in Schultz creek. This is a very small fraction, although these numbers are not normalized for length of channel. The length of channel along which the 15,000 m^3 of sediment was distributed is unclear; therefore it is impossible to make a direct comparison of sediment volumes in the Schultz Burn area and in Schultz Creek.

The volume of sediment eroded and transported can be limited by the volume of sediment available (Moody and Martin, 2009) Sediment production on hillslopes can be a limiting factor if high-magnitude precipitation is frequent enough to flush channel sediments out of high relief, mountainous watersheds over a prolonged period. Potential future changes in climate were not considered when performing this study, but if there was a prolonged period of high-magnitude precipitation that reduced available sediment on hillslopes, there would likely still be ample sediment available for transport remaining in the main channel. In other words, Schultz Creek is currently a transport-limited system, not a weathering- or erosion-limited system. The volume of sediment mobilized and transported depends on the magnitude of storm event and is not limited by sediment availability.

2.3.3 - Rate of Deposition

Rate of deposition or sedimentation is dependent on landscape position, and while there were no local records from similar watersheds for comparison, an attempt was made to establish rates for this study. Rates of sedimentation in this study area were determined at trenches 6 and 7 located in the uppermost reaches of Schultz Creek. Schultz Creek sedimentation rates range from 1.65 to 5.27 cm/1000 yrs during the mid-late Holocene from 3112 to 109 yr B.P. The average rate of deposition is 0.430 mm/year (4.30 cm/1000 yr) for trench 6 and 0.394 mm/year (3.94 cm/1000 yr) for trench 7. Richardson's (2003) alluvial chronology of small alluvial fans near Flagstaff indicated that sedimentation rates on the fans were relatively low during the mid-Holocene, from 10-20 cm/1000 years. During the late Holocene, fan aggradation increased to just over 50 cm/1000 year. Joyal (2004) correlated charcoal ages across three sites in northern Arizona to determine a sedimentation rate of 670 cm/1000 yr when the region-wide period of aggradation was initiated. The Schultz Creek sedimentation rates are much smaller Joyal's (2004) and Richardson's (2003) rates. The Schultz Creek rates are the same order of magnitude as Richardson's, a difference potentially due to difference in watershed location. Joyal's rate is very high, possibly due to geographic location (closer proximity to the Mogollon Rim) or limited charcoal age constraints in field areas. It can be concluded that sedimentation rates in the headwaters of Schultz Creek have remained relatively constant and slow throughout the late Holocene; despite minor variability, all rates are the same order of magnitude and relatively low compared to other regional rates.

Chapter 3 - Hydraulic Modeling

INTRODUCTION

Estimating sediment transport, erosion, and aggradation, is notoriously challenging in ephemeral channels following wildfire. The hydrologic and sedimentary responses to wildfire are predominantly a function of burn severity and precipitation (Robichaud et al., 2000). Sediment availability is one of the major controls on rates of erosion, and sediment flux on hillslopes is the greatest source of increased erosion following wildfire (Canfield et al., 2005). Wildfire increases sediment availability by exposing bare soil and by elimination of stabilizing root structures, increasing erodibility. The variability of soil infiltration rates and erodibility complicates predictions of sediment availability (Moody et al., 2013; Scott, 2006).

The spatial and temporal variability of precipitation in arid and semi-arid regions, particularly on watersheds with high relief, further complicates post-wildfire sediment response (Moody et al., 2013; Scott, 2006; Smith et al., 2011). Erodibility on burned watersheds does not have a linear relationship with rainfall intensity (Moody et al., 2013; Yatheendradas et al., 2008).

Abnormally high runoff rates are common on recently burned watersheds, causing higher and flashier peak flows which increase bedload and suspended sediment capacities, often resulting in hyperconcentrated flows (Robichaud et al., 2000; Scott, 2006). Hyperconcentrated flows are non-Newtonian in nature, meaning they have a much higher transport capacity for sediment than Newtonian flow (Scott, 2006). Most current methods used to predict sediment transport were developed for perennial flow, and assume Newtonian flow, which is defined by Scott (2006) as a linear relationship between the shear stress from fluvial action and the resulting rate of shear upon sediments. Many transport formulas are also designed to predict equilibrium sediment transport in steady uniform flow (Hummel et al., 2012). Sediment transport in ephemeral channels, even prior to disturbance from fire, is generally unsteady, also known as nonequilibrium transport, also described as “step-wise” by Scott (2006). This means that fluvial sediments do not respond immediately to changing flow conditions. There is often a lag time, resulting in pulses of sediments as opposed to continuous sediment transport (Hummel et al., 2012; Moody and Martin, 2009). Responses to fire will also vary depending on regional factors including climate, terrain, and vegetation, and the few predictive sediment transport formulas that have been developed for ephemeral flow conditions are not widely applicable, generally only appropriate for individual regions (Scott, 2006; Moody et al., 2013).

Predicting the magnitude, location, and route of sediment transport is very important for preventing hazards to communities adjacent to watersheds prone to fire and post-fire flooding, and to mitigate potential environmental impacts. If one-fourth to all of the Upper Rio de Flag were to burn, the risk of post-fire flooding could be 2 - 6.6 times larger than the 100-year discharge in downtown Flagstaff which could impact the historical downtown, the university, residential areas, and a large hospital (Figure 6) (Leao, 2005). Flashy discharge poses risks to life and property due to the high magnitudes of flow, the rapid time to peak flow, and the high concentrations of sediments in floodwaters (Robichaud et al., 2000; Yatheendradas et al., 2008; Smith et al., 2011; Hummel et al., 2012; Scott, 2006). Water quality in reservoirs, lakes, and riparian zones is degraded by suspended sediments carried by floodwaters. This can be damaging to aquatic organisms and municipal water users (Robichaud et al., 2000). Floodwaters with high sediment concentrations exert increased force on flow routing and flood retention structures, heightening potential for damage (Scott, 2006; Hummel et al., 2012). Post-fire sediment concentrations also have impacts on the channel morphology which can lead to damages to property on or near the channel. Aggradation increases with larger suspended bedloads, which can elevate the channel floor, constrict the channel, increasing the potential for overbank flooding (Hummel et al., 2012).

Previous Modeling

There have been several hydrologic and hydraulic models created by different entities to assess the potential extent of flooding in the 100-year flood in the Rio de Flag. Different methods and data inputs have been used for each model, resulting in varying results of peak discharges.

USACE (2000) modeled the 2, 10, 25, 50, 100, and 500-year floods in the Rio de Flag using HEC-2 and HEC-RAS. The result of primary interest in this study is the 100-year discharge and what data were used to create the model. Models were created using historic flooding information from USGS gauges, stage data from recent floods, high water marks from the 1993 flood event, and associated rainfall data. Only 19 years of discharge data were available for determining the magnitude of the 100-year flood. The February 1993 storm was three days of rain on snowpack resulting in the highest maximum water surface elevation at Big Fill Lake on record (6763 ft). The model is calibrated to actual observed discharges and stages. This model was used to delineate the floodplain for economic analysis of damages that could occur in Flagstaff. Discharge was reported at several concentration points in the Rio de Flag. Concentration point 1 is just below the confluence of Schultz Creek with the Rio de Flag (Fig. 11), which has a discharge of 1910 ft^3/s for the 100-year flood. USACE also modeled the floodplain with an estimate of urban growth by 2053. At concentration point 1, the 100-year flood peak discharge is 2100 ft^3/s when considering the 50-year build out. This study indicates that the Rio de Flag channel generally only has the capacity of the 2-year to 10-year peak discharge.

The most recent modeling report from FEMA of the 100-year flood was published in 2010 (FEMA, 2010). The Rio de Flag was previously studied by the USACE (1975) and the City of Flagstaff (Arizona Engineering Company, 1979), so FEMA reviewed the hydrology of these reports and adopted the data for the Flood Insurance Study. HEC-1 (USACE, 1973) was used to model peak floodflows. Discharges for "Rio de Flag (West)" were obtained from the City of Flagstaff FIS (1996). The modeled 100-year peak discharge in the Rio de Flag above Crescent Drive is 1300 ft^s/s. Base map information was derived from USGS Digital Quadrangles at 1:12,000 resolution from aerial photography.

It is speculated that the different modeling methods accounts for the disparity between the FEMA and the USACE results (USACE, 2000). The USACE (2000) used actual discharge data and observed stage data, where the FEMA model uses rainfall-runoff modeling.

A few post-burn hydraulic models have been created for the Schultz Burn area. JE Fuller/Hydrology & Geomorphology, Inc. (JEF) was hired by Coconino County to prepare flooding and sediment yield estimates for simulation of a storm event immediately after the burn and after an assumed recovery period of 20 years. FLO-2D was used for all modeling, which is a volume-conservation flood-routing model that routes rainfall-runoff and flood hydrographs in unconfined channels using the dynamic wave approximation to the momentum equation (JEF, 2011). FLO-2D can model sediment transport and spatially variable rainfall and infiltration. Five-, 25-, and 100-year storm recurrence intervals were modeled using SCS curve umbers and NOAA Atlas 14, 24-hour depth rainfall data. A 7-ft DEM was used for topography, a base roughness coefficient of 0.04 was assigned to all floodplain elements. A Level II quantitative geomorphic analysis (ADWR, 1985) was performed to evaluate the potential sediment response. ADWR Level II analysis entails using the Modified Universal Soil Loss Equation (MUSLE) to estimate event based wash load (particles <0.0625 mm, primarily from hillslopes and channel banks) sediment yields for defined runoff events. All MUSLE variables were calculated using the TES for Coconino National Forest. The power-relationship procedure for was selected for estimating bed-material load (>0.0625 mm, channel sediments).

Natural Channel Design (NCD, 2012) performed a study to define the origins and amount of sediment delivered to private lands downstream of the Schultz Burn Area, and to estimate how much sediment can be kept in place or stopped in transport before reaching private lands through channel and watershed restoration practices in the uplands. This study was a follow-up to JE Fuller’s modeling. The study objective was to refine sediment predictions to better understand average annual rates of low and sediment movement for more effective design and construction of flood relief channels. Channel bank data were estimated from visual observation of stream channels using the BANCS model (Rosgen, 2002). Hillslope sediment yield was estimated for this model by the Coconino NF using the ERMiT model. Estimates of sediment transport were made using

FlowSed/PowerSed as programmed in RiverMorph v5 beta (Rosgen, 2006). Beaver Creek Experimental Watershed data were used to create flow duration curves and suspended sediment curves. Data were from watersheds with similar climatic, hydrologic, soil, and vegetation conditions as the Schultz Burn area. Bankfull discharge was estimated with a 1.5 year return interval event, suggested to be an average return interval within the region by other research. The results of this study revealed that there is a lot of unstable sediment remaining in channels that could readily be transported in future storm events, and that alluvial fans could be good locations to store sediment if transport through fresh gullies in alluvial fans is prevented. NCD suggests channel reconstruction of single-thread channels to disperse sediment laden flow and promote sediment storage on alluvial fans and areas with slopes <10%. With certain appropriately applied sediment reduction practices, NCD predicted that active aggradation could continue for 25-100 years.

3.1 - METHODS

There is a paucity of data available for this watershed: there are no stream gauges in the watershed, and surficial maps are limited to national soil surveys by the NRCS and the Holm (1988) geologic map. The NRCS soil maps do not have sufficient accuracy of spatial complexity of soils (see section 1.3.2 for details). The geologic map (Holm, 1988) does not differentiate between Quaternary deposit types, and until summer of 2013 the only topographic data available was the USGS 10 ft contour DEM. Due to the lack of available data, very little was known about the fluvial dynamics of the watershed. Surficial mapping and surveys of channel geometry were conducted as a part of this thesis to improve modeling results.

3.1.1 - Program Selection

Modeling sediment transport in ephemeral channels is very challenging due to the non-Newtonian nature of runoff and pulsation of sediment movement. A model was also desired that could be shared with the Forest Service and the City of Flagstaff to be adapted and used in the future, requiring that the software selected be widely recognized and effective for this environment.

A few different models have been designed to model event-based channel mobilization and erosion. Kineros2 (Goodrich, et al., 2012) is an event-based watershed rainfall-runoff and erosion model that has been successfully calibrated for pre- and post-fire hillslope erosion and sediment transport in channels in the arid Walnut Gulch experimental watershed near Tucson, AZ (Canfield and Goodrich, 2006) and a Starmer Canyon near the 2011 Las Conchas Fire, NM (Canfield et al., 2005). Kineros2 is used with the ArcGIS-based Automated Geospatial Watershed Assessment (AGWA) tool, which automates watershed delineation and performs initial parameterization of watershed elements using national GIS data layers. Watershed elements are estimated as planes and trapezoidal channels with no curvature and limited topographical resolution, which has been found to induce excess infiltration and distort runoff patters and sediment fluxes (Lopes and Canfield, 2004). Kineros2 requires detailed land cover data from nationally available databases such the TES which is not very detailed and incomplete in some cases for the Schultz Creek area. Kineros2 also requires precipitation inputs from rain gauge observations which are not available for Schultz Creek. Kineros2 would only able be able to very coarsely estimate the Schultz Creek topography and would likely underestimate sediment yield, and has only been calibrated successfully in an arid desert environment. For these reasons, Kineros2 was not deemed appropriate for this research.

HEC-RAS is a widely utilized one-dimensional hydraulic model that can calculate water surface profiles for steady and unsteady flow in natural channels. Basic computational procedures are based on the solution of the energy equation and Manning's equation. The momentum equation is used when the water surface profile is rapidly varied. HEC-RAS is freely available and open to the public from the Hydrologic Engineering Center (USACE, 2006). The newest version of HEC-RAS has a sediment transport package which will contribute to analysis of sediment mobilization potential for the watershed. The early version of the sediment model, HEC6T, was used to describe changes in channel scour and deposition in ephemeral channels after the 2000 Cerro Grande fire in New Mexico, which was in a semi-arid watershed forested with ponderosa pine and volcanic dacite substrate, similar to Schultz Creek (Canfield et al., 2005; Earles et al., 2004). There are several different sediment transport equations to choose from in HEC-RAS, and studies have shown that Yang's equation is appropriate for post-fire sediment transport in ephemeral channels (Canfield et al., 2005; Yang et al., 1991; Hummel et al., 2012). HEC-RAS has the option of modeling sediment in quasi-unsteady flows, also termed nonequilibrium transport, which is typical of post-fire flows on burned watersheds (Hummel et al., 2012). HEC-RAS meets all the needs of this research and is also open-source and nationally used, it was deemed the most appropriate tool for this study. The Watershed Modeling System (WMS) version 8.4 was used as the Graphical User Interface (GUI) for channel geometry construction (Aquaveo, 2010).

3.1.2 - Hydrology

The hydraulic modeling scenarios are based on hydrologic modeling done by the Forest Service for the FWPP. The Forest Service modeled runoff and peak discharge on an unburned and unthinned forest, and a wildfire in different forest structures resulting from the various FWPP treatment alternatives. Alternative 3 was not modeled because it is too similar to Alternative 2 and differences would likely be negligible. Soil burn severity maps were produced with fire behavior model FlamMap, the same model that was used to model fire behavior for the 4FRI Draft Environmental Impact Statement (USDA, 2013). Soil burn severity categories were defined by heat/unit area (kilojoules/m^2). The heat/unit area ranges for each burn severity category (high, moderate, low, and very low/unburned) were determined based on the Schultz Fire soil burn severity percentages. Thirty-nine% of the Schultz Fire was high burn severity, so the top 39% of the heat/unit area fire outputs for a wildfire on the Dry Lake Hills were designated as high burn severity heat/unit area values.

Hydrologic modeling was conducted for Schultz Creek with WildCat5 (Hawkins and Barreto-Munoz, 2013). WildCat5 uses burn severity outputs with the curve number (CN) method. This technique uses hydrologic soil classifications based on minimum infiltration rates derived from the Terrestrial Ecosystem survey (TES) data. The CN method has been widely utilized since the 1950's as a rainfall-runoff hydrology tool, created by the USDA Soil Conservation Service (now the NRCS). CN is a transformation of the maximum possible difference between the runoff depth and event rainfall depth to be a measure of runoff response to rainfall (Hawkins et al., 2010). CN values have been assigned to NRCS Hydrologic Soil Groups, cover conditions, and land use by various agencies and published studies. CNs have been determined to be more accurate on agricultural and urban landscapes than on wild or natural landscapes. CNs can be used to calculate runoff from a specific recurrence interval rainfall event, to generate time-distributed runoff pulses from time-distributed rainfall in hydrograph models, and can be applied in continuous soil moisture models. Kirpich's equation was used to calculate the time of concentration (Singh, 1992).

CNs were selected from published literature (USDA, 1986) and adjusted to generate a peak discharge similar to what would result from the 100-year flood identified by FEMA for Schultz Creek (FEMA, 2010). Two storm events were used; a 100-year flood modeled in WildCat5 (Hawkins and Barreto-Munoz, 2013) and the precipitation event on July 20, 2010 which resulted in the most intense runoff from the Schultz Burn area (results summarized in table 6). The 100-year flood is from the USGS Streamstats (http://water.usgs.gov/osw/streamstats/), 4.91 inches in 24-hours, modeled using a Soil Conservation Service (SCS) type II storm distribution. An SCS Type II storm distribution reflects the typical behavior of storms in the western United States (Figure 30) (Ponce, 1989). The 100-year flood is a 1% probability storm, which is possible but very statistically rare. The July 20th storm was a high-intensity, short-duration storm (1.78 inches in 45 minutes), and is a very typical and statistically likely precipitation event with a 10-year recurrence interval. Unburned and thinned runoff conditions were not modeled. Although thinning treatments might locally impact surface cover and infiltration, there will be buffers of undisturbed areas which will absorb excess runoff. There would be minimal differences in peak discharge on unburned forests of any density.

HEC-RAS requires initial flow data for at least one point of concentration in the channel per channel reach. The hydrologic modeling performed by the Forest Service for the entire Schultz Creek watershed were not sufficient, but the Forest Service modeling methodology was replicated for each point of concentration along the channel (each cross section). Curve numbers were selected for unburned current conditions based on TES Hydrologic Soil Group and Vegetation using USDA curve numbers (USDA, 1986) (Table 7). All vegetation groups were considered "woods" with good cover (woods protected from grazing, and litter and brush adequately cover the soil) except for montane/subalpine grassland, which was considered "pasture" with good cover (>75% ground cover and light or only occasionally grazed). Curve numbers for wildfire scenarios were selected based on soil burn severity from the Forest Service fire behavior modeling outputs and TES Hydrologic Soil Groups. Curve numbers for each soil burn severity were based on modeled peakflow responses of the Cerro Grande Fire in NM (Springer and Hawkins, 2005). Composite curve numbers were not used. Composite CNs have been shown to be a flawed method, and can result in artificially low runoff depths (as low as half) than when distributed CNs are used (Grove et al., 1998). Each concentration point contributing area had multiple curve numbers for different acreages of contributing area depending on hydrologic soil groups and soil burn severity or vegetation type (aka, distributed CNs). Table 8 shows curve numbers.

The Forest Service modeled hillslope erosion using the Erosion Risk Management Tool (ERMiT). ERMiT is a web-based tool developed by the U.S. Forest Service based on the Water Erosion Prediction Project (WEPP) for predicting post-fire erosion rates on hillsopes (Robichaud et al., 2007). ERMiT predicts sediment delivery to streams from rill and interrill erosion. Soil textures were selected based on TES and soil burn severity

Table 6. Peak discharge (Q) results from WildCat5 hydrologic modeling performed by the Forest Service for Schultz Creek. (Runyon, 2014). The FEMA peak discharge for the 100-year flood is what was modeled at the outlet of Schultz Creek.

Model Scenario	FEMA 100-Year Peak Q (cfs)	100-year Peak Q (cfs)	Schultz Rain Event Peak Q (cfs)
No thinning action, current conditions, unburned	440	474	222
No thinning action, wildfire	N/A	2045	2014
FWPP Alternative 2, wildfire	N/A	1184	804
FWPP Alternative 4, wildfire	N/A	1607	1409

Table 7. Curve numbers for unburned conditions based on cover type and hydrologic soil group (USDA, 1986).

	Hydrologic Soil Group		
Cover Type	B	C	D (rock)
Woods (good)	55	70	95
Pasture (good)	61	74	95

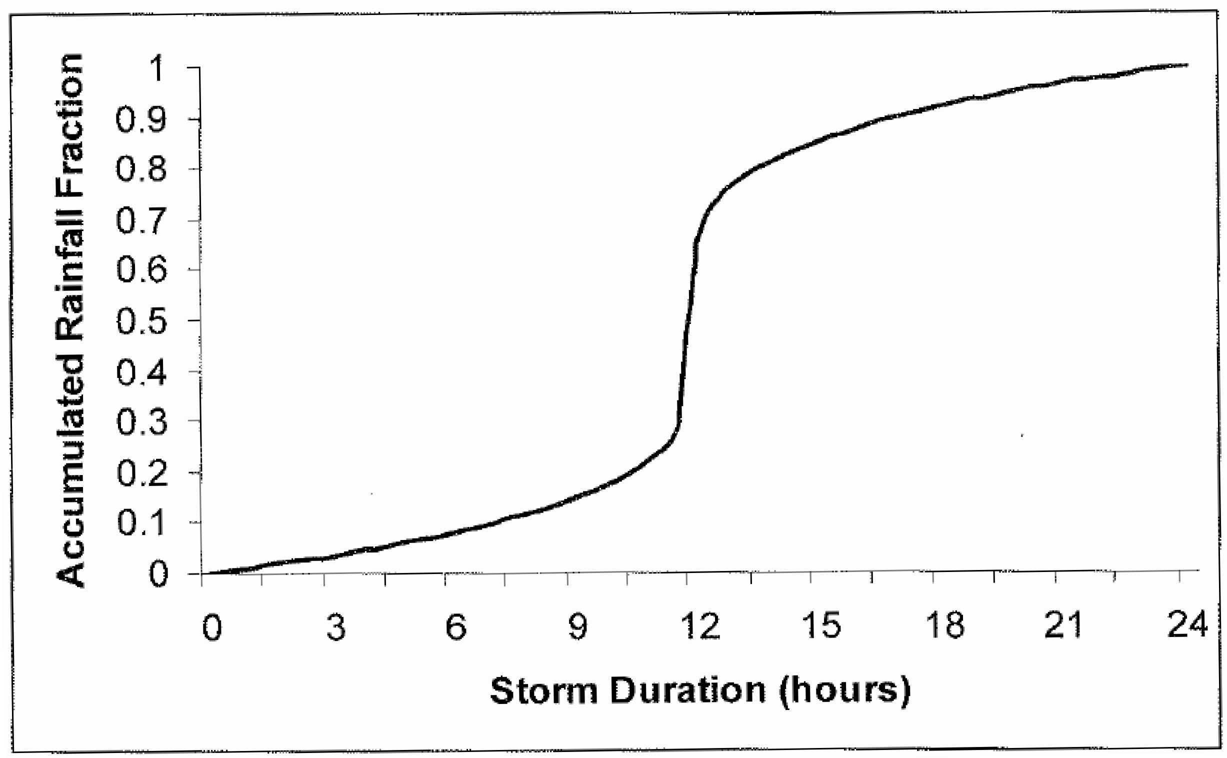


Figure 30. SCS Type II, 24 hour rainfall distributions. The accumulated rainfall fraction is the ratio of the cumulative rainfall at any time to total 24 hour rainfall. (Leao, 2005)

Table 8. Curve numbers for soil burn severity based on hydrologic soil group.

Hydrologic Soil Group/Soil Burn Severity	Curve Number
B	
high	91
low	68
moderate	80
very low/unburned	50
C	
high	92
low	74
moderate	83
very low/unburned	55
D (rock)	95

Table 9. ERMiT post-fire annual hillslope delivery results. % Delivery Change compares the difference in sediment delivery probability with that from the no action wildfire alternative. The % sediment delivery is the probability that a sediment delivery rate will be equaled or exceeded in the first year following wildfire (Runyon, 2014)

Model Scenario	Total Sediment Delivery (tons)	% Sediment Delivery Change
No thinning action	14912	0
Alternative 2	8277	-44
Alternative 4	12977	-13

from the soil burn severity models. Climate input data were from the Fort Valley Experimental Forest weather station (http://www.fs.fed.us/rm/fort-valley/). Total annual sediment delivery for different treatment alternatives are reported in table 9. ERMiT does not model event-based hillslope sediment yield, therefore the results cannot be incorporated into the HEC-RAS model.

3.1.3 - Channel Geometry

Cross sections were measured or derived from existing data to construct channel profiles for the hydraulic model. The City of Flagstaff obtained aerial LiDAR surveys with 2 ft resolution during the summer of 2013 with a small buffer around the city. This extends into the lower portion of the Schultz Creek watershed about 5,230 m along the axial channel, covering about 7 km^2 (39%) of the total watershed area. Coconino County has aerial LiDAR with 1 ft resolution for select portions of the county including the upper portion of the Schultz Creek watershed. Channel cross sections were measured by hand with measuring tapes and a hand bubble level. Measuring tapes were stretched out across the channel perpendicular to the thalweg. A bubble level was fixed on one stream bank and directed at the equivalent elevation on the opposite bank of the stream to level the measuring tape. A cross section was measured approximately every 250 m of channel, with additional cross sections when a 250 m mark coincided with a major knick point (Cross sections 8a/b and 13a/b) (Fig 15). The widths of the cross sections were determined in the field to capture the terraces and their depositional units (when present) and a small portion of the flood plain (when present). Depths were measured at least every 50 cm of width using a measuring tape, with additional measurements where complex topography was present. Depths are accurate to the nearest 0.5 cm. Locations of the cross sections were recorded on the GISPro (v. 2.1.1) app (Garafa, LLC, Provo, UT) on an Ipad 4. Geomorphic units in cross section were defined, and terrace elevations above the modern channel were noted.

Valley cross sections were approximated by determining the steepest slope of the valley walls at the same locations of measured channel cross sections and extending them into ‘V’ shape beneath the channel cross section (Fig 14). Bedrock in alluvial channels in steep terrain is assumed to erode into a ‘V’ shape. Images from debris flows off the 2010 Schultz Burn area show low-order channels with this morphology (Figure 4b). The valley cross sections with aerial LiDAR coverage were measured using ArcMap. Valley cross sections without LiDAR coverage were measured manually using a Topcon Laser Level and stadia rod. Vertical (elevation) controls were established at ground locations as near as possible to the channel cross section locations using a Leica CS25 Global Navigation Satellite System (GNSS) receiver. The GNSS receiver was configured to provide a Real-Time Network (RTN) kinematic GNSS position using cellular data service provided by Verizon, or access to the Arizona Continuously Operating Reference Station (AZCORS) network. The nearby AZCORS station AZFL, located on the NAU campus, was utilized. GNSS-determined ellipsoid heights were reduced to NAVD88 (North American Vertical Datum 1988) elevations using the GEOID09 model.

To estimate the total sediment available to be mobilized in the Schultz Creek channel, each two-dimensional sediment profile was assumed to be constant along a length of channel bracketing each cross section. Each cross section was considered the midpoint for its length of channel.

3.1.4 - Roughness Coefficients

A range of potential Manning's roughness coefficients were estimated for Schultz Creek (Table 10). Broad differences in roughness of the main channel and the floodplain of the different reaches were determined visually based on vegetation, litter cover, and substrate grain size. Chow's (1959) roughness coefficient values for natural streams were used as a guide.

3.1.5 - HEC-RAS Boundary Conditions

3.1.5.1 - Steady State Flow

The normal depth based on known channel thalweg gradients was used to define the boundary conditions for steady state flow simulations. Normal depth and peak flow was defined for each cross section. Mixed sub- and super-critical flow regime was selected.

Table 10. Manning's roughness coefficients used for HEC-RAS hydraulic simulations.

Reach	Cross Section	Channel n	Overbank n
Upper Headwaters	18	0.05	0.08
	17	0.05	0.08
Lower Headwaters	16	0.05	0.08
	15	0.05	0.08
	14	0.05	0.08
	13a	0.05	0.08
Middle Reach	12	0.045	0.075
	11	0.045	0.075
	10	0.045	0.075
	9	0.045	0.075
	8a	0.045	0.075
Lower Reach	7	0.04	0.07
	6	0.04	0.07
	5	0.04	0.07
	4	0.04	0.07
	3	0.04	0.07
Alluvial Fan	2	0.04	0.07
	1	0.04	0.07

3.2 - RESULTS

3.2.1 - Flood Hydraulics

To define a channel for simulation with HEC-RAS requires inputs of channel geometry, discharge data, and Manning's roughness values at designated cross sections. HEC-RAS simulates numerous hydrologic parameters of the channel using these data including shear stress, water velocity, energy slope, flow area. Only a few of these outputs were relevant to the discussion in this thesis. Full results from HEC-RAS simulations are available in Appendix D.

The steady state runs of the models were performed using a mixed sub- and super-critical flow regime. The flow volumes (ft^2) of different model scenarios were compared to assign a metric to define efficacy of different treatments' abilities to reduce flood risk. The primary goal was to determine how much post-fire flow could be reduced by each of the FWPP treatments compared to unthinned conditions. This was accomplished by determining what percentage of unthinned flow volume the flow volume was for each thinning alternative for each storm-type (table 11). At the confluence of flow (cross section 1), Alternative 2 was more effective at reducing flow volume than alternative 4 for both storm types. For a 100-yr storm, alt. 2 reduced flow volume by 38.5%, alternative 4 by 20.8%. In a Schultz-type storm, alt. 2 reduced flow volume by 55.1%, alt. 4 by 26.3%. The Schultz-type storm is much more typical of the monsoon season with a 10-yr recurrence interval, therefore is more germane for determining potential flooding. Considering that, the model predicts that FWPP alternative 2 is ~29% more effective than alternative 4 at decreasing flow volume at the confluence of Schultz Creek.

Table 11. Difference in post-fire flow area compared to unthinned watershed (%). Gradational color intended to illustrate relative differences between alternatives. Lighter color indicates the highest percentage of mitigated flow volume.

		100-yr storm		Schultz-type storm	
Cross Section	Reach	Alt 2	Alt 4	Alt 2	Alt 4
18	U.H.	-38.6	-1.8	-51.0	28.6
17		-21.9	4.3	-41.7	18.1
16		-25.9	-8.9	-46.4	-6.5
15	L.H.	-19.7	-0.9	-39.2	1.1
14		-28.0	-8.6	-49.7	-1.8
13		-22.8	0.7	-40.8	4.9
12		-29.5	-6.0	-49.7	-6.4
11		-26.0	-4.1	-51.1	-9.3
10	M.R.	-19.6	-2.8	-43.1	-10.1
9		-27.4	-6.8	-45.4	-14.5
8		-23.1	-5.9	-44.2	-11.3
7		-34.7	-18.3	-52.3	-21.9
6		-27.4	-6.1	-44.6	-18.2
5	L.R.	-26.8	-11.3	-42.7	-17.2
4		-29.4	-9.9	-63.0	-17.8
3		-26.7	-13.1	-44.1	-19.0
2	A.F.	-34.7	-15.9	-54.9	-20.4
1		-38.5	-20.8	-55.1	-26.3
Total average:		-27.8	-7.6	-47.7	-8.2

Increase in flow
<2% decrease
2-10%
10-20%
20-35%
35%+

Figure 31 depicts water surfaces at cross section 1 from each forest condition after a wildfire and a Schultz-type storm (10-yr RI). The model results indicates that both alternative 2 and 4 effectively reduce flow compared to untreated conditions, but alternative 4 is significantly less effective than alternative 2. At this location on the alluvial fan, the channel is large enough to contain the discharge from all burn scenarios included in this study. Because this study included no analyses of the channel in the alluvial fan downstream of cross section 1, it is not clear if the channel downstream of this cross section is capable of conveying these flows.

Upstream of the alluvial fan at cross section 2, where the channel is still confined by a bedrock valley, the channel is much smaller. Modeling indicates that if Schultz Creek does not receive any forest treatments and burns, a 10-yr storm could result in up to 1.5 ft of water on the floodplain of cross section 2 which spans approximately 150 ft in width. Model results indicate that alternative 2 mitigates ~30% of channel overflow at cross section 2, but there would still be significant flooding.

The channel flows through a 28 inch culvert 0.2 miles downstream of cross section 1. No hydraulic analysis was performed at the culvert, but the discharge simulated by the model for all post-burn scenarios would be greater than could be accommodated by the culvert (Figure 31). Modeled flow velocities at cross section 1 were high: 20.04 ft/s for untreated, 19.98 ft/s for alternative 4, and 17.67 ft/s for alternative 2. Further analysis is needed to determine the effects these magnitudes of flows would have on infrastructure such as culverts, but it can be stated with confidence that the culvert is likely an impedance to flow.

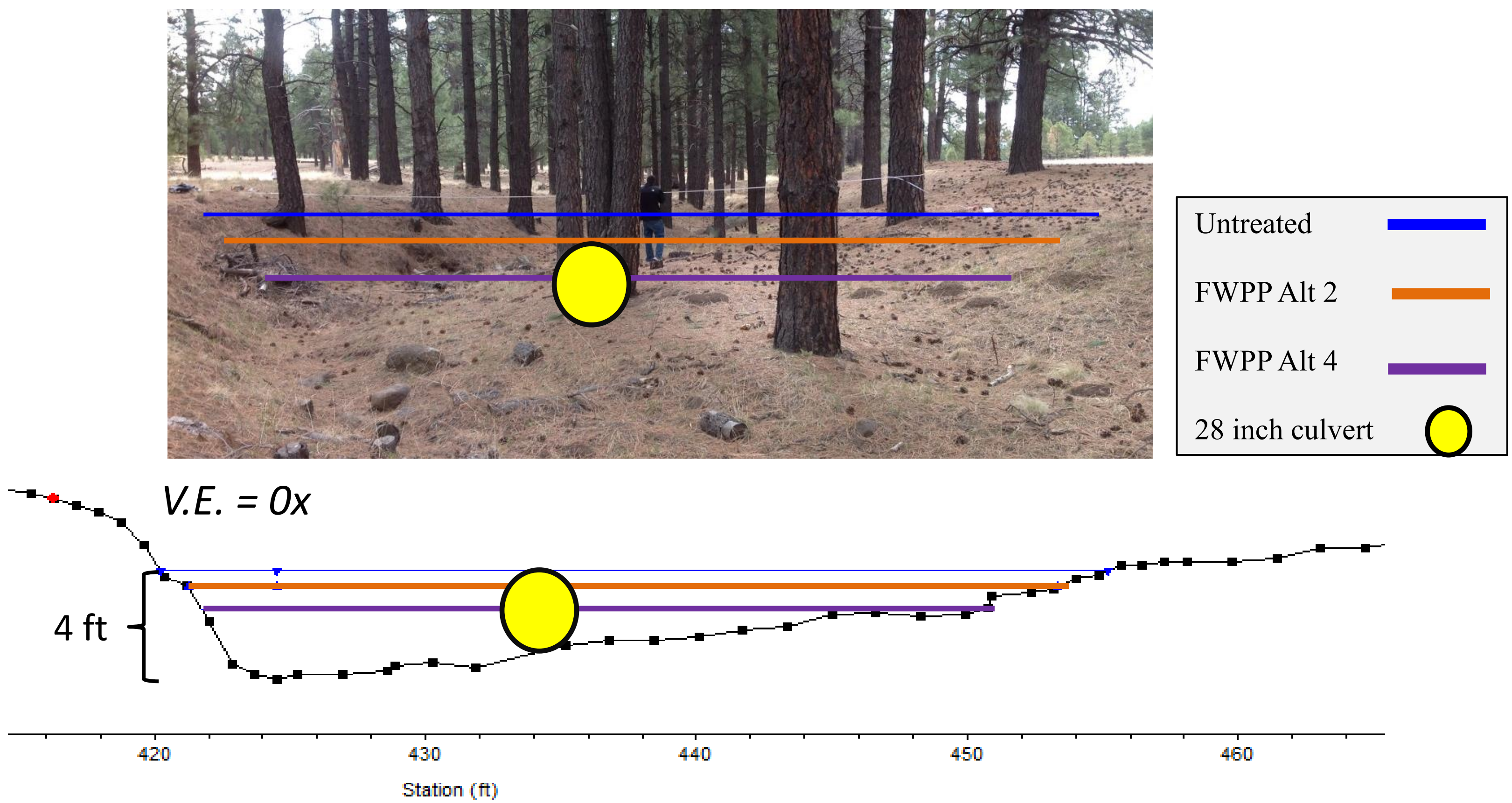


Figure 31. HEC-RAS water surfaces for a 10-yr storm at cross section 1. The yellow circle shows the actual size of the 28” culvert 0.2 miles downstream of this location.

3.3 - DISCUSSION

Several inputs for the HEC-RAS simulations of Schultz Creek were based on previous modeling done in other programs by different entities. There are several assumptions made by using these various inputs that could have affected the model, introduced sources of error, and possibly limited the accuracy of the results.

Hydrologic modeling in WildCat5 was very sensitive to Curve Number selection. Hawkins (1976) published curve numbers determined from real data from the Beaver Creek Experimental watershed in Arizona. When using these data to estimate curve numbers instead of the empirically derived curve numbers that were used in this study, the peak discharge results varied drastically. A hydrograph was produced in WildCat5 for Cross Section 12 using curve numbers developed using data from the Beaver Creek Experimental Watershed (Hawkins, 1976) to compare with the hydrograph produced using empirically derived curve numbers that were used in this study. The peak discharge from the 100-year flood using the data-based curve numbers is 1272 ft^3/s, whereas the peak discharge with the empirically derived curve numbers is 469 ft^3/s. This large difference indicates that the empirically derived curve numbers underestimate the amount of runoff on natural, semi-arid, forested land.

CN methods have been criticized for several reasons. A constant (the Initial abstraction ratio) in the equation used to determine all existing handbook CN tables has been found to include a much larger range of numbers, making all handbook CN values of dubious value compared to more recently published, data-based CN values.CN methods are also subject to scrutiny due to the limited parameterization. It is well understood that there are complex natural controls on rainfall-runoff relationships, and

CN numbers only have input information for a select few of these parameters. CNs are almost completely empirical and not based in fact, limiting the application and effective use of this method.

There were data deficiencies preventing model calibration and subsequent sediment modeling. Roughness coefficient selection is challenging and subject to significant scrutiny without observed rainfall/runoff data for calibration. No gauge data are available for Schultz Creek, therefore accuracy of selected roughness coefficients is unknown. Flow data including either total discharge or velocity with observed water surfaces would be required to calculate roughness coefficients.

There were several cross sections where the water surface defaulted to the critical depth. This is most likely due to the relative low density of cross sections on such steep slopes (~2-5%). It is recommended, at a minimum, cross section geometry should be measured every 50 ft (Willie Odem, personal communication). The model built for this study was intended to be a comparative analysis of possible flow scenarios and not an accurate simulation of a specific condition because no stream discharge calibration data exist for Schultz Creek. The results are a useful preliminary analysis of the hydraulics along Schultz Creek and were not developed for use as a detailed design tool. Future studies could significantly improve simulation with more detailed field work and monitoring. Geometry resolution could be improved by converting available LiDAR data for the watershed into a HEC-RAS friendly format to extract cross section data within HEC-RAS. Detailed monitoring of observed runoff events could be used to calibrate a model to discharge measurements.

The compounding of many modeling assumptions and gaps in data rendered the model developed in this study unreliable to simulate sediment transport. Modeling for this study is directly reliant on previous modeling such as the burn severity modeling and hydrologic modeling conducted by the Forest Service. All modeling involves some, if not many, assumptions. Each time modeling results are used to inform a subsequent model, assumptions are compounded. It was not possible to compute the compounded modeling uncertainty of the approach used to build HEC-RAS in this study. To construct a high-quality sediment transport model, more data and improved hydrologic inputs are required.

The estimation of the volume of stored sediment in the channel and on the flood plain would be improved with verification of depth to bedrock in multiple locations of the watershed. Either physical excavation to bedrock and/or geophysical techniques could be used to better estimate depth to bedrock. An analysis of the quantitative grain size distributions of the entire alluvial sediment thickness throughout the watershed needs to be conducted. As sediments erode, buried sediment will be exposed and needs to be considered in a sediment transport model. Another limitation of the hydraulic model is that several small culverts along the channel were excluded because their simulation was beyond the scope of the study. The addition of culverts and other structures would further improve the model if it were updated with additional data and monitoring.

A sediment transport model would need to include event-based hillslope sediment transport due to the significance of post-fire hillslope sediment yield. Hillslope sediment contributions to the main channel would be an important component of total sediment yield from the watershed and could affect hydraulic processes. In addition to monitoring of discharge data, sediment yield monitoring, both on hillslopes and in the channel, would be valuable to calibrate a sediment transport model. If combined with flow data, a rainfall/runoff/sediment yield relationship could be developed for the watershed to allow for model calibration. Some additional literature review beyond that presented in this study would be required to determine how that relationship could change in the event of a wildfire.

Future studies could consider using the Yang sediment transport equation (Yang et al., 1991). This equation is believed to be the most effective for modeling post-fire sediment transport on ephemeral landscapes (Canfield et al., 2005; Yang et al., 1991; Hummel et al., 2012).

3.3.1 - Discharge

There have been numerous studies on potential 100-year flows in the Rio de Flag watershed from different sources most notably FEMA (2010) and USACE (2000). Peak discharge results are slightly different; FEMA's peak discharge near the former USGS Crescent Drive gauge is 1450 cfs, and USACE's modeling indicated 1910 cfs. Both studies are limited due to the short period of gauge data (19 years at the Crescent Drive gauge) which was used to determine the appropriate magnitude of the 100-year storm. Only the FEMA 100-year discharge was used in Forest Service post-fire modeling; using other predicted 100-year discharge such as USACE would vary the results of post-fire runoff modeling, likely by increasing modeled flooding extents.

3.3.2 - FWPP Land Surface Classification

The Forest Service used TES soil types for hydrologic modeling and hillslope erosion models, and map units with multiple complexes were simplified to only represent the dominant component or complex, or to represent the most conservative value for a particular attribute, such as erodibility (Runyon, 2014). Based on this method, the simplification was designed to lead to a conservative estimate of runoff or hillslope erosion, meaning is meant to be an overestimate rather than an underestimate of hazards. Even so, this oversimplification of an already limited resolution surficial map could have resulted in inaccurate representation of surface cover, and possibly inaccurate or oversimplified model results.

3.3.3 - Hillslope Sediment Yield

The Forest Service modeled annual hillslope erosion rates for the treatment areas, but did not model any post-fire event-based hillslope sediment yields (table 9). Increased hillslope sediments is known to be the most dramatic flux in sediment yield post-fire (Canfield et al., 2005), even though channels are still the dominant source of sediments in post-fire runoff (Moody and Martin, 2009). Accounting for hillslope sediment inputs to the channel in hydraulic modeling would likely influence the results of predicted discharge and erosion. The forest service modeled annual erosion rates, but no event-based hillslope sediment yield modeling

Chapter 4 - Summary of Results and Discussion

4.1 - Results and Implications

4.1.1 - Alluvial chronology

Local climate during the late Holocene was variable and in flux according to bristlecone pine dendrochronology study in the San Francisco Peaks (Salzer, 2000). In the 1,419 year record, 42 extreme intervals were identified when both climate and precipitation varied significantly from mean conditions. The entire record is in figure 29. 72% of the local extreme dry periods and 48% of the local extreme wet periods overlap with similar precipitation extremes for west-central New Mexico, suggesting that these were regional episodes rather than local. The San Francisco Peaks climate showed both local and regional scale variations during this period of record.

Local and regional climate studies were used to interpret the depositional history of the Schultz Creek watershed with age constraints provided by charcoal radiocarbon ages. There are a few major thresholds and events evidenced by the geomorphology and sediment records of this watershed: (1) the period of aggradation for Unit 1; (2) initiation of the series of debris flows deposited in the Lower Reach; (3) incision of Unit 1; (4) deposition of Unit 2.

Unit 1 represents a long, relatively consistent period of aggradation along the main channel. This is supported by the thickness of the unit, the (non-stratigraphic inversion) of charcoal ages, its consistent presence along a majority of the main channel, and lack of bedding or stratigraphy. The sediments resemble deposits at a site on the Mogollon rim studied by Joyal (2004) – dark brown, unstratified, cumulic soil, believed to be deposited prior to 1970± yr B.P. during a regionally recorded period of steady aggradation. The oldest charcoal fragment taken from Unit 1 is 6585 cal yr B.P. (year

4572 BC) (Figure 2.7.5). This correlates to the end of a major incisional event evidenced in sediment records across the northern Arizona region that occurred sometime prior to 6000 yr B.P (Joyal, 2004; Anderson et al., 2003; Neff et al., 2003). In Walnut Canyon (~2015 m), about 21km away from the base of the San Francisco Peaks (2,134 – 3,851 m), the incisional period ended earlier, around 8000 yr B.P. (Neff et al., 2003). The regional period of aggradation began later at sites closer to the Mogollon Rim, aka at lower elevations (Joyal, 2004; Anderson et al., 2003).

This was around the transition to the mid-Holocene thermal maximum. Paleoclimate records from northern Arizona in places such as Potato Lake (2222 m elevation) (Anderson, 1993) and Stoneman Lake (2050 m) (Hasbargen, 1994) evidence very warm and dry conditions from approximately 8000 to 4000 yr B.P. The records at Walker Lake (2700 m) has a record of the lowest water record in 20,000 years at about 6000 yr B.P., probably the peak of the dry period in the San Francisco Peaks region (Hevly, 1985). The dry period probably allowed sediments to aggrade because more sediments could be stored on hillslopes without being immediately eroded and washed out of watershed as they were during the preceding wet period when erosion was the predominant process.

The warm and dry conditions of the mid-Holocene were interrupted sometime around 2000 yr BP (Hevly, 1985), and the late-Holocene was generally cool and wet (Weng and Jackson, 1999). Modern analogues indicate that cool and wet conditions in this region result in high runoff and erosion (Salzer, 2000), although there is no clear evidence of erosion in Schultz Creek until the late 1800’s.

The radiocarbon dates for the charcoal sampled from debris flow deposits in the lower reach range from 313 to 608 cal yr B.P. (Table 3). The dates from the debris flow deposits do not provide insight into the precise timing of deposition, other than the fact that each debris flow must post-date the formation of charcoal from its deposit. The top of the debris flows are higher in elevation than Unit 1. It is unclear where the bases of the debris flows are, but Unit 2 seems to have been deposited around the debris flows. It is possible that there were several low-magnitude fires in the uplands of the Schultz Creek watershed between 300 and 600 cal yr B.P., and the debris flows occurred sometime after 313 yr B.P. (year 1700) when the climatic conditions were suitable. Hereford (2002) has identified a period from A.D. 1400 to 1880, correlative with the Little Ice Age (LIA), during which valley-fill alluvium deposition was widespread across the southern Colorado Plateau. Regionally, climatic conditions were relatively cool and dry. This period of region-wide alluviation is attributed to a long-term decrease in high magnitude floods. In other words, before and after the LIA, high-magnitude flooding was much more frequent and alluviation was not always possible due to erosive flooding. The debris flows could have resulted from over-saturated soils, only possible with low-magnitude high-frequency precipitation that would have occurred during this period.

There are many possible causes of debris flow initiation, including rainfall. Primary climatic factors such as intense rainfall or snowmelt can directly trigger debris flows. These events can lead to rapid infiltration causing soil saturation and temporary increase in soil pore pressure, potentially causing debris flows or landslides. Secondary climatic factors can also influence debris flow initiation such as antecedent rainfall or snowmelt, which can increase potential for debris flow initiation during intense rain (Wieczorek and Glade, 2005).

Local climate studies point to high climatic variability during the LIA period (Salzer, 2000), but there is consensus between local and regional climate and sediment studies that high magnitude flooding was common at the end of the 1800's until the late 1930s (Hereford, 2002).

The youngest charcoal fragment extracted from Unit 1 is 109 yr B.P. (year 1904) (Figure 17). There is no evidence in this dataset to suggest that the period of aggradation during deposition of Unit 1was dramatically slowed or interrupted prior to 109 yr B.P. The shift from an aggradational to an erosional system probably began sometime around or after 109 yr B.P. in the Schultz Creek watershed. This date corresponds to an increase in effective precipitation from A.D. 1907-1926 following drier conditions that had persisted for 33 years (Salzer, 2000), an increase in the frequency of large floods (Hereford, 2002), and subsequent erosion across northern Arizona (Hereford, 1984). Climate did play a role in the high-magnitude incision at the turn of the 19th century, but this was also due in part to anthropogenic forcing. Thousands of cattle were introduced to the region in 1875, and were overstocked by 1880 (Masek Lopez and Springer, 2002). Overgrazing and drought in the mid-1890's significantly reduced vegetative cover, resulting in increased runoff and erosion and severe downcutting of streams (Hereford 1984). Unit 2 is less clearly defined than Unit 1 and is less consistently present along the main channel. The charcoal ages in Unit 2 do not exceed 602 cal yr B.P. and are mostly younger than the oldest charcoal ages preserved in the top of adjacent Unit 1 deposits (Figure 18, 19).

Unit 2 probably consists of sediment reworked from the top of Unit 1 and deposited in the active channel after the period of dramatic incision of Unit 1 ceased. Unit 2 sediments were probably not transported far downstream from their source locations on the terrace surface of Unit 1reflects erosional responses to more local climatic forcing. Incision of Unit 1 and deposition/reworking of Unit 2 is still actively occurring at the present (Summary of alluvial chronology in table 5).

4.1.2 - Sediment Volume

Previous sediment yield simulations were compared to the simulations developed with this study. The Forest Service simulated the mass of annual hillslope sediment delivery (tons). After a wildfire in Schultz Creek watershed with no wildfire, 14,912 tons of hillslope sediment yields are estimated in the first year post-fire, according to the ERMiT modeling performed by the Forest Service (Runyon, 2014). Synthesis of post-fire sediment yield literature has revealed that approximately 25% of post-fire sediment is sourced from hillslopes, and the remaining 75% from channels. If we assume that 14,912 tons is only 25% of the total potential sediment yield, the approximate total sediment yield would be 59,648 tons, with 44,736 tons being sourced to the channel. Total stored sediment in the Schultz Creek channel is estimated to be 1,531,791 tons. Total stored sediment would not necessarily be mobilized; this mass reflects what is *available* for transport. 44,736 tons is only about 1% of the estimated total sediment stored in the channel. There are several possible explanations for the disparity between the stored channel sediments and the Forest Service hillslope sediment modeling. It is possible that the hillslope sediment yields are underestimates due to modeling assumptions, or the sediment volume estimates in this study are overestimates due to overestimates of bedrock depth. The soil bulk density value (1.57 g/cm^3) used for the sediment in Schultz Creek could be an overestimate, although the low end of soil bulk density values for sandy loams is about 1.40 g/cm^3. When using 1.40 g/cm^3 as the soil bulk density, the mass of stored channel sediments is still the same order of magnitude (~1.3 million tons), so the mass of sediment is not very sensitive to soil bulk density. There is a lot of coarse material in the channel sediments ranging from cobbles to boulders, but solid rocks have a bulk density of 2.65 g/cm^3 (Arshad et al., 1996), so taking this into account would only increase the mass of stored channel sediments.

The appropriateness of the bedrock cross sectional morphology and the resulting stored sediment volume is likely in the correct range, but could be improved with a more exhaustive literature review or collection of additional field data, such as geophysical surveys of the sediment thickness stored in channels. The assumption of a “V” shaped bedrock channel for stored channel sediment volume estimates was used to simplify the channel geometry. If the bedrock channel is actually a “U” shape, the volume estimate resulting from this study could be under or overestimates depending on the depth of the bedrock erosion. A limited literature review indicated some models for determining rates of bedrock erosion, although there does not seem to be any specific law about the shape a bedrock channel will erode into. According to the models, it depends on numerous factors such as climate, the channel slope, the geology, discharge, average grain size and bedload sediment supply, drainage area, and vegetation (Montgomery and Buffington, 1997; Seidl and Dietrich, 1992; Finnegan et al., 2005; Wobus et al., 2006). Although it is out of the scope of this project, one of the erosion models could be used to simulate erosion of bedrock in conditions that could have caused bedrock erosion in the study area to improve sediment volume estimates. As an alternative to modeling, observation of bedrock morphology of a channel denuded of sediment with similar climate, slope, and geology as the study area would improve estimates of sediment volume. Probing to depth of the bedrock in the study area or implementation of shallow geophysical techniques could also help improve the sediment volume estimate.

Major erosion after the Schultz Fire in July 2010 resulted in scouring down to bedrock at some locations of the channel, with maximum scour depth about 4 meters deep. My inferred bedrock depth beneath stored channel sediments ranges from 1.4 to 8.8 m, with mean of 4.9 m, so the sediment volume estimation method used in this study is feasible. It is unlikely that all sediment stored in the channel would be mobilized in one runoff event, or even over the course of one monsoon season, post-burn. After the first monsoon season post-Schultz Fire, it was estimated that 15,000 m^3 of sediment had been recently disturbed and was unstable but had not yet exited the channel network (Carroll, 2011). There were also large volumes of sediment stored directly adjacent to the main channel (in channel banks) that were predicted to be mobilized in future high runoff events, but generally remained in place following the monsoons of 2010. The estimated volume of stored sediments for Schultz Creek in this study includes active channel sediments and channel bank sediments, therefor it is not an estimate of sediment that necessarily would or could be mobilized in a single post-burn runoff event, simply a volume of unconsolidated sediments stored in and directly adjacent to the main channel. The estimate of total stored sediment in Schultz Creek is equal to approximately to 884,600 m^3. 15,000 m^3 is only about 1.7% the estimated stored sediment in Schultz creek. This is a very small fraction, although these numbers are not normalized for length of channel. The length of channel along which the 15,000 m^3 of sediment was distributed is unclear; therefore it is impossible to make a direct comparison of sediment volumes in the Schultz Burn area and in Schultz Creek.

The volume of sediment eroded and transported can be limited by the volume of sediment available (Moody and Martin, 2009). Sediment production on hillslopes can be a limiting factor if high-magnitude precipitation is frequent enough to flush channel sediments out of high relief, mountainous watersheds over a prolonged period. Potential future changes in climate were not considered when performing this study, but if there was a prolonged period of high-magnitude precipitation that reduced available sediment on hillslopes, there would likely still be ample sediment available for transport remaining in the main channel. In other words, Schultz Creek is currently a transport-limited system, not a weathering- or erosion-limited system. The volume of sediment mobilized and transported depends on the magnitude of storm event and is not limited by sediment availability.

4.1.3 - Rate of Deposition

Rate of deposition or sedimentation is dependent on landscape position, and while there were no local records from similar watersheds for comparison, an attempt was made to establish rates for this study. Rates of sedimentation in this study area were determined at trenches 6 and 7 located in the uppermost reaches of Schultz Creek. Schultz Creek sedimentation rates range from 1.65 to 5.27 cm/1000 yrs during the mid-late Holocene from 3112 to 109 yr B.P. The average rate of deposition is 0.430 mm/year (4.30 cm/1000 yr) for trench 6 and 0.394 mm/year (3.94 cm/1000 yr) for trench 7. Richardson's (2003) alluvial chronology of small alluvial fans near Flagstaff indicated that sedimentation rates on the fans were relatively low during the mid-Holocene, from 10-20 cm/1000 years. During the late Holocene, fan aggradation increased to just over 50 cm/1000 year. Joyal (2004) correlated charcoal ages across three sites in northern Arizona to determine a sedimentation rate of 670 cm/1000 yr when the region-wide period of aggradation was initiated. The Schultz Creek sedimentation rates are much smaller Joyal's (2004) and Richardson's (2003) rates. The Schultz Creek rates are the same order of magnitude as Richardson's, a difference potentially due to difference in watershed location. Joyal's rate is very high, possibly due to geographic location (closer proximity to the Mogollon Rim) or limited charcoal age constraints in field areas. It can be concluded that sedimentation rates in the headwaters of Schultz Creek have remained relatively constant and slow throughout the late Holocene; despite minor variability, all rates are the same order of magnitude and relatively low compared to other regional rates.

4.1.4 - Modeling

4.1.4.1 - Results

To define a channel for simulation with HEC-RAS requires inputs of channel geometry, discharge data, and Manning's roughness values at designated cross sections. HEC-RAS simulates numerous hydrologic parameters of the channel using these data including shear stress, water velocity, energy slope, flow area. Only a few of these outputs were relevant to the discussion in this thesis. Full results from HEC-RAS simulations are available in Appendix D.

The steady state runs of the models were performed using a mixed sub- and super-critical flow regime. The flow volumes (ft^2) of different model scenarios were compared to assign a metric to define efficacy of different treatments' abilities to reduce flood risk.

The primary goal was to determine how much post-fire flow could be reduced by each of the FWPP treatments compared to unthinned conditions. This was accomplished by determining what percentage of unthinned flow volume the flow volume was for each thinning alternative for each storm-type (table 11). At the confluence of flow (cross section 1), Alternative 2 was more effective at reducing flow volume than alternative 4 for both storm types. For a 100-yr storm, alt. 2 reduced flow volume by 38.5%, alternative 4 by 20.8%. In a Schultz-type storm, alt. 2 reduced flow volume by 55.1%, alt. 4 by 26.3%. The Schultz-type storm is much more typical of the monsoon season with a 10-yr recurrence interval, therefore is more germane for determining potential flooding. Considering that, the model predicts that FWPP alternative 2 is ~29% more effective than alternative 4 at decreasing flow volume at the confluence of Schultz Creek.

Figure 31 depicts water surfaces at cross section 1 from each forest condition after a wildfire and a Schultz-type storm (10-yr RI). The model results indicates that both alternative 2 and 4 effectively reduce flow compared to untreated conditions, but alternative 4 is significantly less effective than alternative 2. At this location on the alluvial fan, the channel is large enough to contain the discharge from all burn scenarios included in this study. Because this study included no analyses of the channel in the alluvial fan downstream of cross section 1, it is not clear if the channel downstream of this cross section is capable of conveying these flows.

Upstream of the alluvial fan at cross section 2, where the channel is still confined by a bedrock valley, the channel is much smaller. Modeling indicates that if Schultz Creek does not receive any forest treatments and burns, a 10-yr storm could result in up to 1.5 ft of water on the floodplain of cross section 2 which spans approximately 150 ft in width. Model results indicate that alternative 2 mitigates ~30% of channel overflow at cross section 2, but there would still be significant flooding.

The channel flows through a 28 inch culvert 0.2 miles downstream of cross section 1. No hydraulic analysis was performed at the culvert, but the discharge simulated by the model for all post-burn scenarios would be greater than could be accommodated by the culvert (Figure 31). Modeled flow velocities at cross section 1 were high: 20.04 ft/s for untreated, 19.98 ft/s for alternative 4, and 17.67 ft/s for alternative 2. Further analysis is needed to determine the effects these magnitudes of flows would have on infrastructure such as culverts, but it can be stated with confidence that the culvert is likely an impedance to flow.

4.1.4.2 – Discussion

Several inputs for the HEC-RAS simulations of Schultz Creek were based on previous modeling done in other programs by different entities. There are several assumptions made by using these various inputs that could have affected the model, introduced sources of error, and possibly limited the accuracy of the results.

Hydrologic modeling in WildCat5 was very sensitive to Curve Number selection. Hawkins (1976) published curve numbers determined from real data from the Beaver Creek Experimental watershed in Arizona. When using these data to estimate curve numbers instead of the empirically derived curve numbers that were used in this study, the peak discharge results varied drastically. A hydrograph was produced in WildCat5 for Cross Section 12 using curve numbers developed using data from the Beaver Creek Experimental Watershed (Hawkins, 1976) to compare with the hydrograph produced using empirically derived curve numbers that were used in this study. The peak discharge from the 100-year flood using the data-based curve numbers is 1272 ft^3/s, whereas the peak discharge with the empirically derived curve numbers is 469 ft^3/s. This large difference indicates that the empirically derived curve numbers underestimate the amount of runoff on natural, semi-arid, forested land.

CN methods have been criticized for several reasons. A constant (the Initial abstraction ratio) in the equation used to determine all existing handbook CN tables has been found to include a much larger range of numbers, making all handbook CN values of dubious value compared to more recently published, data-based CN values.CN methods are also subject to scrutiny due to the limited parameterization. It is well understood that there are complex natural controls on rainfall-runoff relationships, and CN numbers only have input information for a select few of these parameters. CNs are almost completely empirical and not based in fact, limiting the application and effective use of this method.

There were data deficiencies preventing model calibration and subsequent sediment modeling. Roughness coefficient selection is challenging and subject to significant scrutiny without observed rainfall/runoff data for calibration. No gauge data are available for Schultz Creek, therefore accuracy of selected roughness coefficients is unknown. Flow data including either total discharge or velocity with observed water surfaces would be required to calculate roughness coefficients.

There were several cross sections where the water surface defaulted to the critical depth. This is most likely due to the relative low density of cross sections on such steep slopes (~2-5%). It is recommended, at a minimum, cross section geometry should be measured every 50 ft (Willie Odem, personal communication). The model built for this study was intended to be a comparative analysis of possible flow scenarios and not an accurate simulation of a specific condition because no stream discharge calibration data exist for Schultz Creek. The results are a useful preliminary analysis of the hydraulics along Schultz Creek and were not developed for use as a detailed design tool. Future studies could significantly improve simulation with more detailed field work and monitoring. Geometry resolution could be improved by converting available LiDAR data for the watershed into a HEC-RAS friendly format to extract cross section data within HEC-RAS. Detailed monitoring of observed runoff events could be used to calibrate a model to discharge measurements.

The compounding of many modeling assumptions and gaps in data rendered the model developed in this study unreliable to simulate sediment transport. Modeling for this study is directly reliant on previous modeling such as the burn severity modeling and hydrologic modeling conducted by the Forest Service. All modeling involves some, if not many, assumptions. Each time modeling results are used to inform a subsequent model, assumptions are compounded. It was not possible to compute the compounded modeling uncertainty of the approach used to build HEC-RAS in this study. To construct a high-quality sediment transport model, more data and improved hydrologic inputs are required.

The estimation of the volume of stored sediment in the channel and on the flood plain would be improved with verification of depth to bedrock in multiple locations of the watershed. Either physical excavation to bedrock and/or geophysical techniques could be used to better estimate depth to bedrock. An analysis of the quantitative grain size distributions of the entire alluvial sediment thickness throughout the watershed needs to be conducted. As sediments erode, buried sediment will be exposed and needs to be considered in a sediment transport model. Another limitation of the hydraulic model is that several small culverts along the channel were excluded because their simulation was beyond the scope of the study. The addition of culverts and other structures would further improve the model if it were updated with additional data and monitoring.

A sediment transport model would need to include event-based hillslope sediment transport due to the significance of post-fire hillslope sediment yield. Hillslope sediment contributions to the main channel would be an important component of total sediment yield from the watershed and could affect hydraulic processes. In addition to monitoring of discharge data, sediment yield monitoring, both on hillslopes and in the channel, would be valuable to calibrate a sediment transport model. If combined with flow data, a rainfall/runoff/sediment yield relationship could be developed for the watershed to allow for model calibration. Some additional literature review beyond that presented in this study would be required to determine how that relationship could change in the event of a wildfire.

Future studies could consider using the Yang sediment transport equation (Yang et al., 1991). This equation is believed to be the most effective for modeling post-fire sediment transport on ephemeral landscapes (Canfield et al., 2005; Yang et al., 1991; Hummel et al., 2012).

4.1.2.3 - Discharge

There have been numerous studies on potential 100-year flows in the Rio de Flag watershed from different sources most notably FEMA (2010) and USACE (2000). Peak discharge results are slightly different; FEMA's peak discharge near the former USGS

Crescent Drive gauge is 1450 cfs, and USACE's modeling indicated 1910 cfs. Both studies are limited due to the short period of gauge data (19 years at the Crescent Drive gauge) which was used to determine the appropriate magnitude of the 100-year storm. Only the FEMA 100-year discharge was used in Forest Service post-fire modeling; using other predicted 100-year discharge such as USACE would vary the results of post-fire runoff modeling, likely by increasing modeled flooding extents.

4.1.3.4 - FWPP Land Surface Classification

The Forest Service used TES soil types for hydrologic modeling and hillslope erosion models, and map units with multiple complexes were simplified to only represent the dominant component or complex, or to represent the most conservative value for a particular attribute, such as erodibility (Runyon, 2014). Based on this method, the simplification was designed to lead to a conservative estimate of runoff or hillslope erosion, meaning is meant to be an overestimate rather than an underestimate of hazards. Even so, this oversimplification of an already limited resolution surficial map could have resulted in inaccurate representation of surface cover, and possibly inaccurate or oversimplified model results.

4.1.3.5 - Hillslope Sediment Yield

The Forest Service modeled annual hillslope erosion rates for the treatment areas, but did not model any post-fire event-based hillslope sediment yields (table 9). Increased hillslope sediments is known to be the most dramatic flux in sediment yield post-fire (Canfield et al., 2005), even though channels are still the dominant source of sediments in post-fire runoff (Moody and Martin, 2009). Accounting for hillslope sediment inputs to the channel in hydraulic modeling would likely influence the results of predicted discharge and erosion. The forest service modeled annual erosion rates, but no event-based hillslope sediment yield modeling

4.2 - DISCUSSION

4.2.1 - Values and Uses of Research

Surficial mapping, sediment analyses, and hydraulic modeling in this study are complimentary to modeling and analysis that the Forest Service is conducting for the Flagstaff Watershed Protection Project (FWPP) treatment areas. Modeling that is being conducted for the FWPP includes event-based hydrologic modeling and annual hillslope erosion modeling to predict the immediate and long-term effects of wildfire on thinned forests. Hydrologic modeling reflects changes in peak discharges as a result of changes in forest density or soil infiltration rates that could occur from wildfire and/or thinning. Peak discharge outputs from hydrologic modeling are some of the most vital parameters required for any hydraulic modeling effort. Event-based hydraulic modeling, including sediment mobilization, is an important component of these modeling efforts. Event-based models provide some quantitative means to predict what parts of the Rio de Flag would be at the greatest risk of damage from flooding, hyperconcentrated flows, and erosion. Hydraulic modeling predictions would be improved by event-based hillslope erosion modeling.

The Forest Service simulated hillslope erosion for the various forest thinning alternatives and storm scenarios using the Erosion Risk Management Tool (ERMiT). ERMiT is a web-based program developed by the Forest Service to predict annual erosion rates on hillslopes following wildfire (Robichaud et al., 2007). Although the results from this non-event based modeling could not be incorporated into HEC-RAS sediment modeling, the result still provided a data to compare with stored sediment volume estimates

Accurate surficial mapping and estimates of stored sediment are important for understanding the fluvial dynamics of the Schultz Creek channel. In the event of a wildfire, the magnitude of mobilized sediment and erosion from post-fire runoff is a function of channel substrate type, grain size distribution, channel morphology, and depth to bedrock. The more detail available about these channel characteristics, the greater the potential for accurate modeling results.

These data are also a valuable resource on the watershed for emergency mitigation treatment implementation. After the Schultz Fire of 2010, the Burn Area Emergency Rehabilitation (BAER) team had to implement erosion and flood mitigation treatments with very limited knowledge of the watershed and of flooding potential. Some treatments were ineffective, in some cases ended up contributing to damage rather than preventing it. Rock armoring was implemented on certain slopes to control erosion, particularly along the waterline road, but flooding on July 20th was powerful enough to dislodge the rocks, contributing to scouring. Larger rocks may have been effective. The pipeline ended up being damaged in over 20 locations. Farther downslope in the neighborhoods downstream of the burn area, rock gabions were installed in a drainage ditch on an alluvial fan with 4% slope, a transition zone from the piedmont zone of higher slope. Due to location and the transition to lower slopes, flood waters would drop suspended sediment at the decrease in gradient, making runoff onto the fan sediment starved and highly erosive. Gabions were poorly placed and improperly installed, and were ultimately compromised by high flood flows. Flows worked around the sides of the gabions which widened the channel and increased sediment transport (Neary et al., 2011).

With an increased understanding of the sediment transport processes and sediment sources, planning and implementation of downstream damage mitigation is more likely to be effective (Carroll, 2011). The time frame for burn area recovery is riddled with uncertainties and is very challenging to predict, but studies have shown that increased sediment delivery and peak discharges can persist long after the burn even. The greatest increases in erosion occur in the first two years post-fire, with increased sediment yields on low-severity burn areas for three years, and up to 14 years on high-severity burn areas (JE Fuller, 2011).

4.2.2 - Recommendations

Based on knowledge gained from this study about stored sediments, there are some practices that could be implemented to decrease the potential risk of flooding and erosion damage. Along the channel, some stored sediment could be excavated from locations with the most storage, possibly from large knick points. Analysis indicates that the Lower Reach has the most cubic sediment stored per foot of channel (not including the Alluvial Fan). Prevention of property damage risks could also be achieved by preventing development of the alluvial fan and the parcels directly downstream of the watershed. Currently the parcels on the alluvial fan (other than the forest service and private land) are owned by the City of Flagstaff and the Museum of Northern Arizona (Fig. 32). Downstream of the culvert, the channel is deeply incised up to 2.5 meters with dramatically eroded channel banks. This incision could have resulted from lowering of base level due to the position of culvert beneath the downstream extent of the channel. If high flood flows were channelized and flowed into the culvert, it would likely exceed the capacity of the culvert and result in culvert damage and possibly increased flood damage.

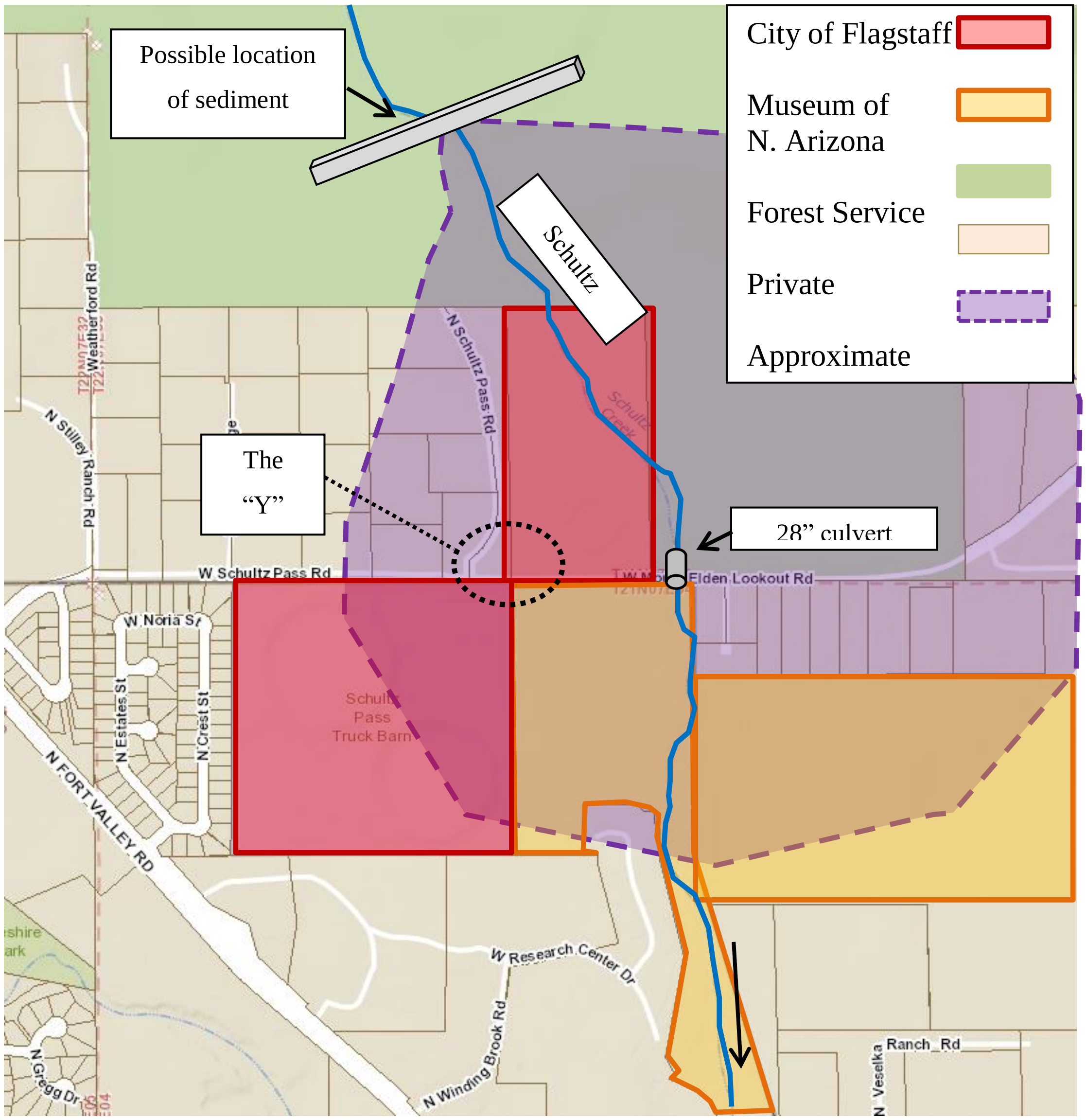


Figure 32. Map of land ownership on the Schultz Creek alluvial fan. https://gismaps.coconino.az.gov/parcelviewer/

The alluvial fan is a high-risk area for flooding and erosion damage. The Timberline neighborhood is developed on top of the alluvial fan for the Schultz Burn watersheds, and was severely damaged by post-burn flooding for many years following the Schultz Fire. The Schultz Creek alluvial fan should under no circumstances be developed.

If the Schultz Creek watershed were to burn, mitigation treatments should be focused on preventing sediment-laden flood flows from scouring the main channel across the fan. Diversion structures at the top of the alluvial fan could be installed to force flood flows to spread out across the top of the fan, forcing water velocities to slow and thus causing suspended sediment to be deposited and stored on the fan. If flood flows and suspended sediment was not dispersed at the head of the fan, it would scour the main channel of the fan, potentially decreasing the width/depth ratio and creating a narrower channel of transport for flood flows. This would only cause flood velocities and stream power to increase as it entered the Rio de Flag and would increase flooding and erosion risk potential in downtown Flagstaff.

A detailed study of the alluvial fan could inform estimates of how much sediment is currently stored in the fan, and how much sediment it could hold in the event of high sediment transport from Schultz Creek. Alluvial fans can be composed of various types of deposits at different fan locations (Bull, 1972). Heavy equipment would be required to examine sediments at depth and at different locations of the fan such as the head, the points of coalescence from different contributing tributaries, and the boundaries. A coarse estimate of volume of sediment currently stored in the alluvial fan could be made by determining difference in elevation between the surface of the fan and the underlying geologic units. Alluvial fan geometry is influenced primarily by climate and surrounding geology, therefore a literature review should be conducted to determine if any studies have been done documenting specific morphologies of alluvial fans in semi-arid climates on volcanic terrain to help with study design.

4.2.2.1 – Monitoring

Monitoring of sediment transport and runoff should be conducted in the Schultz Creek watershed during and following forest treatments, both in the channel and on hillslopes. Monitoring would improve baseline data of the watershed's response to disturbance and could lead to the development of rainfall/runoff/sediment yield relationships. These relationships would be useful in the event of a wildfire for predicting and modeling potential magnitudes of post-fire erosion and flooding. In the event of a wildfire, watershed monitoring could lead to estimates of long-term watershed effects such as annual sediment yields.

Forest treatments can increase hillslope erosion from decreased infiltration and soil productivity and reduced size of soil aggregates (Robichaud et al., 2010). Hillslope erosion can be monitored using silt fences, an economical, simple, and temporary method developed by Robichaud and Brown (2002). A silt fence is a sediment trap made out of a synthetic fabric which allows water but not sediment to pass through making them suitable as temporary sediment detention areas. Fences catch all runoff from a determined contributing area, either bounded by natural features or an artificial boundary such as sheet metal. Sediment must be cleaned out and weighed in situ, then analyzed in the lab for soil moisture content to determine erosion rates. These have been found to be more than 90% effective in trapping sediment yields (Robichaud and Brown, 2002).

Pairs of silt fences should be installed in areas of different runoff regimes throughout the watershed, one in an area undisturbed by treatments, one in a treatment area.

Monitoring channel sediment movement could be achieved with a combination of suspended sediment monitoring and studying changes in bedload sediment storage. Changes in sediment storage in the channel can be monitored without high cost using repeat cross section measurement (Lawler, 1992; Swanson and Fredriksen, 1982). If possible, high resolution repeat LiDAR collection is preferable due to quality and spatial extent of data. Erosion and deposition can be highly localized in the channel (Smith and Dragovich, 2008), so repeat cross section measurement could easily miss significant movement of sediment and changes in channel morphology. Suspended sediment measurements can indicate a relative magnitude of sediment discharge, and should be monitored at the outlet of the watershed.

A rainfall-runoff relationship needs to be developed for this watershed and can be achieved with gauging throughout the watershed. Flowtography is a low impact and effective method to monitor flow in ephemeral channels.

All of these recommended methods should be distributed throughout the watershed, but attention should specifically be paid to the transition from confined channel to alluvial fan. Little is known about how much sediment is stored in the fan and how much more sediment could be stored there if there was significant sediment transport from the watershed to the fan.

4.2.3 - Future Research

This study established baseline data for the Schultz Creek watershed. There is more work that could be done to strengthen the understanding of the history of watershed, the modern fluvial dynamics, and the potential for post-fire erosion. The detail of the alluvial chronology could be improved by (a) increased trenching depth and number of locations to collect more charcoal samples and examine character of sediments below the modern channel (b) dendrochronology, and (c) watershed-specific historical documentation.

Increased trenching frequency along the main channel and increased trenching depth would be valuable for collection of more charcoal samples for age constraints on deposits and heightened resolution of soil deposits along the channel longitudinal profile. Larger soil pits at different locations across the main alluvial fan could reveal the various coalescing fan components from the adjacent watersheds. This kind of trenching would require heavy equipment.

Dendrochronology has been used in conjunction with alluvial sediment records to reconstruct past fire regimes in similar climatic/vegetative settings (Bigio et al., 2010). Increased knowledge of periods of frequent fires in the uplands and tributary sub-watersheds could help to interpret the depositional history of the watershed.

Examining primary historical documents about land use specific to the Schultz Creek watershed might provide insight into extents of grazing and timber harvesting, which would have been areas of increased sediment availability in the early 1900's when it is believed that erosion increased in this watershed, and is known to have increased across the region. There is physical evidence of land use at the turn of the 19th century remaining in the watershed today, including old barbed wire, concrete foundations for human habitation or livestock shelter, old rusted cans, and old growth ponderosa pine stumps that were hand logged.

Using curve numbers for hydrologic modeling is an inherently flawed method. Curve Numbers have been criticized for several reasons including initial inaccuracies of constants in the equation, lack of actual data used for their derivation, and limited use of parameters that influence runoff processes (Hawkins et al., 2010). If curve numbers are used, they should be based on real data, not empirically derived numbers as were used in this study.

The estimate of the volume of stored sediment in the channel could be improved with more extensive literature review and some type of ground penetrating field work or geophysics to determine more accurate depth to bedrock. The depth to bedrock and bedrock morphology are major factors in the sediment volume estimate. A limited literature review indicated some models for determining rates of bedrock erosion, although there does not seem to be any specific law about the shape a bedrock channel will erode into. According to the models, it is dependent numerous factors such as climate, the channel slope, the geology, discharge, average grain size and bedload sediment supply, drainage area, and vegetation (Montgomery and Buffington, 1997; Seidl and Dietrich, 1992; Finnegan et al., 2005; Wobus et al., 2006). Although it is out of the scope of this project, one of the erosion models could be used to simulate erosion of bedrock in conditions that could have caused bedrock erosion in the study area to improve sediment volume estimates. As an alternative to modeling, observation of bedrock morphology of a channel denuded of sediment with similar climate, slope, and geology as the study area would improve estimates of sediment volume. Manually probing to depth of the bedrock in the study area could also help improve the estimate of sediment volume estimate, although this would be very disruptive and require heavy equipment. Ground Penetrating Radar could be another viable option for determining the actual depth to bedrock. Accessibility of equipment on the terrain could be a major impediment to achieving either of these suggested methods.

The quality of the hydraulic modeling could be improved with calibration of the model over time. There is currently no gauging equipment in the Schultz Creek watershed, dramatically limiting options for calibrating a model with rainfall/runoff data. Installation of flow monitoring is strongly recommended to increase understanding of fluvial dynamics of the watershed, as well as provide a means of monitoring changing flow conditions in response to thinning. Flowtography would be a relatively cheap and non-disruptive way to monitor ephemeral flows in the channel. Suspended sediment monitoring would be another valuable component of flow condition monitoring, and could be used to calibrate the model's sediment transport predictions.

Addition modeling downstream of Schultz Creek that includes modeling of flow routing structures, city utilities, and other infrastructure could provide enough information to do a cost analyses of damage that could be sustained in after wildfire on different forest conditions. This would be a powerful policy tool and would be an excellent study to disseminate to other municipal governments that could implement a similar funding mechanism to reduce the risk of post-fire flooding. Financial metrics are a very universally understood measure of the success of forest restoration and watershed protection.

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