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Post-fire rill and gully formation, Schultz Fire 2010, Arizona, USA

Daniel G. Neary [a,*], Karen A. Koestner [a], Ann Youberg [b], Peter E. Koestner [c]

[a] USDA Forest Service, Rocky Mountain Research Station, 2500 Pine Knoll Drive, Flagstaff, AZ 86001, USA
[b] Arizona Geological Survey, 416 Congress Street, Suite 100, Tucson, AZ 85701, USA
[c] USDA Forest Service, Rocky Mountain Research Station, Tonto National Forest, 2324 East McDowell Road, Phoenix, AZ 85006, USA

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ABSTRACT

The Schultz Fire burned 6100 ha on the eastern slopes of the San Francisco Peaks in northern Arizona. The fire burned between June 20th and 30th, 2010, across moderate to very steep ponderosa pine and mixed conifer watersheds. About 40% of the fire area was classified as high-severity, mostly on mountain slopes greater than 30% and in places exceeding 100%. The upper slopes rise to over 3300 m and are the source for high energy water, coarse sediments, and woody material. A series of flood events beginning in mid-July 2010 initiated erosion that removed substantial soil from the upper slopes of the watersheds. The second event was characterized by a peak rainfall of 24 mm in 10 min. Substantial amounts of soil were eroded out of a newly developed rill and gully system, removing the A horizon and much of the B horizon. Prior to the fire there were no rills or gullies as the soil was protected by a thick O horizon. This protective organic layer burned off during the fire leaving the soil exposed to raindrop impact and erosion. There was widespread occurrence of high severity fire, with some watersheds classified as 70% high severity wildfire. This left most of the soils with moderate to severe water repellency. The development of an extensive rill and gully network fundamentally changed the hydrologic response of the upper portions of every catchment. The intense, short duration rainfall of the 2010 monsoon interacted with slope, water repellency and extensive areas of bare soil to produce flood flows an order of magnitude in excess of flows produced by similar pre-fire rainfall events. The rill networks now cover much of the upper slopes and gullies are beginning to cut to bedrock. Sediment delivery to the channel systems is likely to continue unabated for many years and hydrologic response will continue to be flashy.

1. Introduction

1.1. Background

Watersheds that have been severely denuded by a wildfire are often vulnerable to accelerated rates of soil erosion and, therefore, can yield large of post-fire sediment (DeBano et al., 1998; Neary et al., 2005). Changes in the hydrologic cycle caused by wildfire affect the rate of soil erosion (Mermut et al., 1997). These erosion processes in turn often alter the hydrologic responses of watersheds, reducing the time of runoff concentration and the magnitudes of flows. The subsequent transport and deposition of the eroded soil as sediment affects water quality, land surface geomorphology, and human habitations and infrastructure (Ice et al., 2004).

The Schultz Fire burned 6100 ha on the eastern slopes of the San Francisco Peaks, a dormant Middle Pliocene to Holocene-aged stratovolcano in northern Arizona (Figs. 1 and 2). The fire burned in the Coconino National Forest between June 20th and 30th, 2010, across moderate to very steep ponderosa pine and mixed conifer watersheds on the east flank of the Peaks (Figs. 3 and 4). About 40% of the fire area was classified as high-severity, mostly on mountain slopes greater than 30% and in places exceeding 100% (Fig. 5). The upper slopes rise to over 3300 m and are the source areas for high energy water, coarse sediments, and woody material. A steep gradient of nearly 1000 m exists from the upper slopes to the base of the lower alluvial fans. Summer thunderstorms tend to develop over the mountain due to orographic lifting. Over the course of an active 2010 Monsoon during July and August, 2010, rainfall was the fourth highest in the Monsoon precipitation record. The Schultz Fire burned area received numerous precipitation events that were a mixture short-duration and long duration storms with low and high rainfall amounts (Fig. 6). The largest event occurred on July 20th and was characterized by a peak rainfall of 24 mm in 10 min, resulting in numerous debris flows, historic floods and substantial hillslope erosion.

Flood flows, after the Schultz Fire, were estimated to be one to two orders of magnitude larger than those produced by similar pre-fire rainfall events. Determining the magnitude and frequency of flood flow events in this landscape is difficult since there were no localized pre-fire rain gage networks or perennial streams with flow gages

* Corresponding author.
E-mail address: dneary@fs.fed.us (D.G. Neary).

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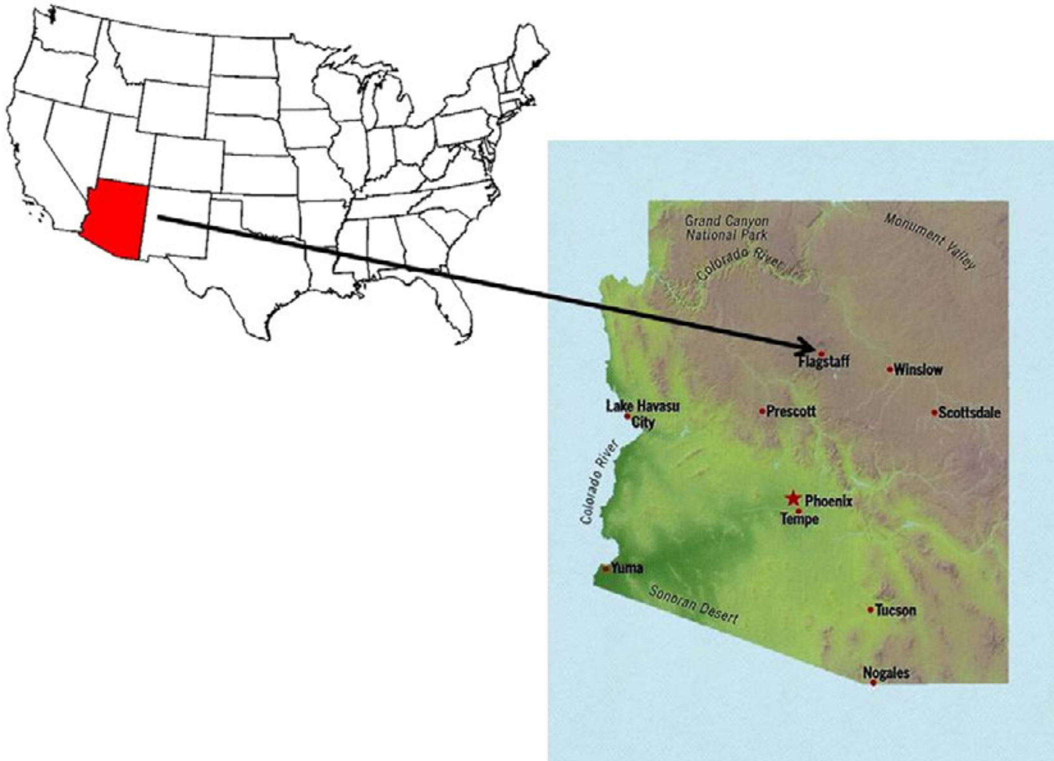

Fig. 1. Schultz Fire location northeast of Flagstaff, Arizona, USA.

prior to the fire. In addition, few historical records exist of flood flows off of the burned landscape although there are clearly defined watersheds and channels on the alluvial fan below the mountain slope. There is geomorphic evidence that flood flows of the sizes observed after the Schultz Fire have not occurred since the last Sunset Crater eruption in the 11th Century A.D. (Conway et al. 1998). Thus, the erosion observed on the upper slopes of the Schultz Fire watersheds described in this paper is also on the scale of a 1000 year return period.

1.2. Objectives

The upper slopes of the San Francisco Peaks have gradients ranging from 60 to >100%. These areas developed unprecedented erosion

Fig. 2. San Francisco Peaks stratovolcano, Coconino National Forest, north central Arizona, USA (Photo courtesy of the American Geophysical Union).

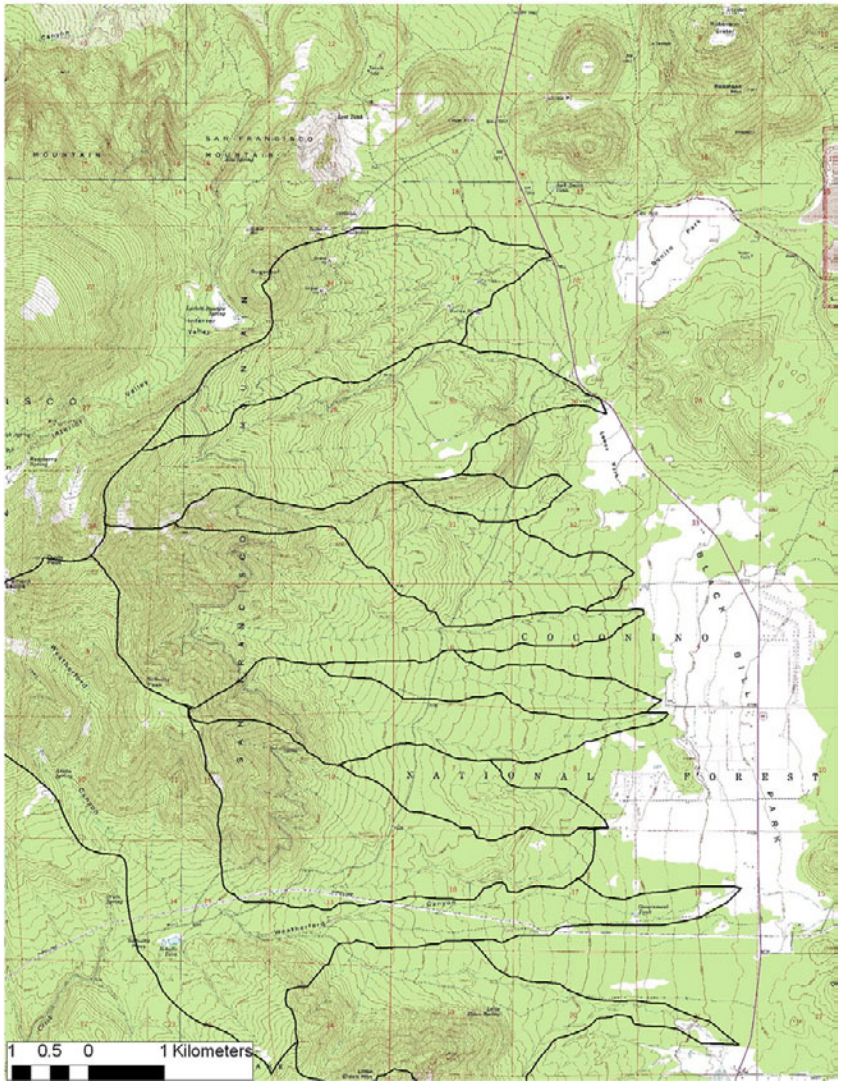

Fig. 3. Principal watersheds and topography of the east flank of the San Francisco Peaks, Arizona, burned by the Schultz Fire of 2010.

after the intense July 20, 2010, storm. The objective of this study was to evaluate the extent and degree of new rill and gully formation, reactivation of old gullies, and how this network contributes to the substantially altered hydrologic response of the upper mountain slopes post-fire (Nations and Stump, 1981).

2. Materials and methods

2.1. Fire location

The San Francisco Peaks are located on the Colorado Plateau of Arizona, within the boundaries of the Coconino National Forest. The mountain is a Middle Pliocene to Holocene-aged stratovolcano that rises to 3851 m. It consists of six peaks above 3400 m that are the remnants of a larger peak that was reduced by volcanic eruptions 400,000 years ago and repeated glaciations since (Nations and Stump, 1981).

2.2. Vegetation

The Schultz Fire burned through three forest types. It started in ponderosa pine (*Pinus ponderosa*), and then went into mixed conifer and spruce-fir stands. Smaller pieces of grassland and alpine tundra were also involved. The dominant vegetation type within the fire was the ponderosa pine/Arizona fescue (*Festuca arizonica*) type followed by a mixed conifer forest of white fir (*Abies concolor*) and Douglas-fir (*Pseudotsuga menziesii*). Effective vegetative ground cover was generally more than 60% (duff layer, needles and grass cover). Herbaceous vegetation was dominated by Arizona fescue bunchgrasses and mountain muhly (*Muhlenbergia montana*) in the ponderosa pine vegetation types. The mixed conifer and spruce-fir types are found at higher elevations (generally above 2430 m) and with herbaceous understory cover dominated by grasses and herbs and litter cover above 90% overall.

2.3. Geology

The geologic units within the Schultz Fire perimeter include volcanic rocks and unconsolidated deposits that range in age from Holocene- to Middle Pliocene-aged at 0–4 million years before present (Ma). These are mapped as volcanic rocks, (QTv), basaltic rocks (QTb) and younger surficial deposits (Q, 0–2 Ma) (Fig. 7; Haessig, 2010). A small amount of Paleozoic sedimentary rocks are found as outcrops at the base of Mount Elden to the south of the fire area. The youngest volcanic rocks are the rhyolite of Sugarloaf Mountain (about 0.22 Ma). The lithology of this unit includes rhyolitic ash, pumice and lapilli. The majority of the volcanics are dacitic volcanic flows of Schultz and Dole peaks. Andesitic flows are found along the

Fig. 4. Schultz Fire burned area on the east flank of the San Francisco Peaks, Coconino National Forest, Arizona, USA, July 2010. (Photo by Daniel G. Neary).

lower portions of the mountain slope. Volcanic rocks comprise 4750 ha (78%) of the area, and surface water and wind deposits make up the remaining 1345 ha (22%) of the fire area. The surface Quaternary deposits (0–2 Ma) consist of unconsolidated to strongly consolidated alluvial fan and eolian deposits (Fig. 7). This unit includes coarse, poorly sorted alluvial fan and terrace deposits on middle and upper piedmonts and along large drainages, and sand, silt and clay on alluvial plains and playas. Wind-blown sand deposits (QTb in Fig. 7) are found downwind of the mountain.

The geomorphology of the eastern *bajada* of the San Francisco Peaks is comprised of steep upper slopes with 100% gradients, and broad, thick fan deposits of a piedmont, alluvial fan, and outwash plain. The piedmont, alluvial fan, and outwash plain consist of sorted

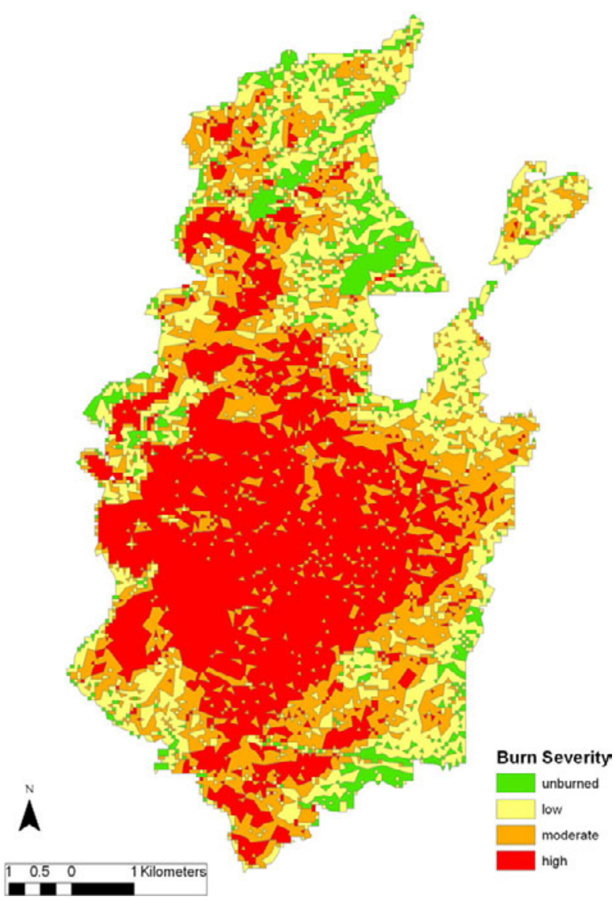

Fig. 5. Burn severities produced by the Schultz Fire, Coconino National Forest, Arizona, June 20–30, 2010.

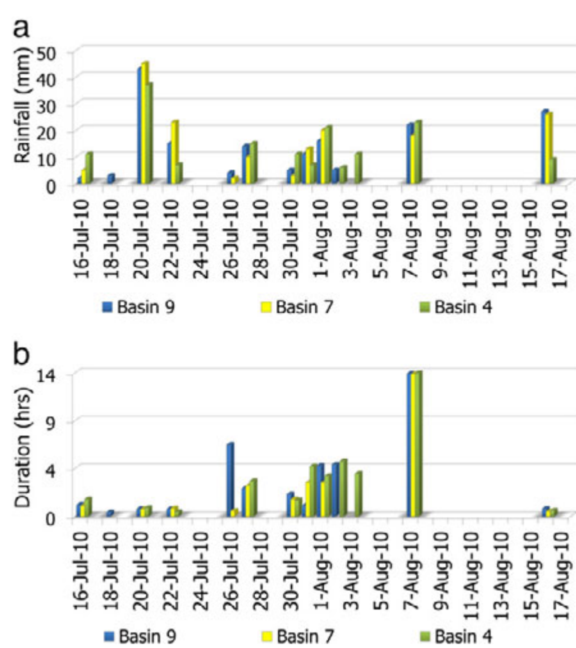

Fig. 6. Schultz Fire 2010 Monsoon rainfall statistics by: a) storm totals and b) storm duration. Storms on July 20th and August 1st produced debris flows.
(Adapted from Youberg et al. 2011).

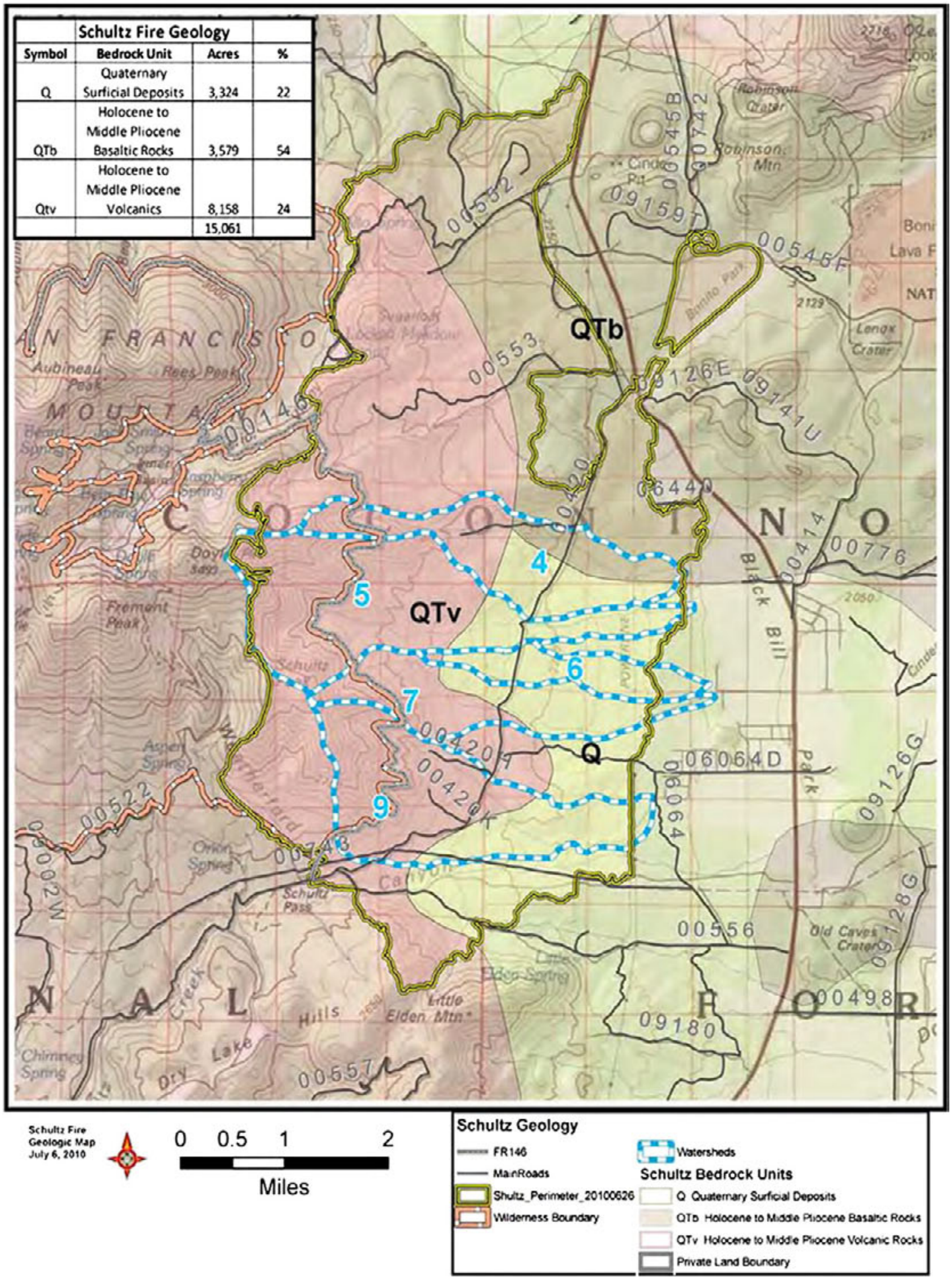

Fig. 7. Geologic units of the east side of the San Francisco Peaks, Coconino National Forest, Arizona, USA. Adapted from Haessig, 2010.

alluvium, colluvium, glacial till, glacial outwash, and eruption lahar deposits mantling the andesite, dacite, and basalt volcanic flows. Surface deflation, rill formation, and gully development were the dominant erosion processes on the upper slopes. Erosion on the piedmont and alluvial fan areas was dominated by channel incision and deposition. Private lands below the Coconino National Forest boundary are developed on top of these alluvial fan deposits (Q in Fig. 7) which have been previously tilled for agriculture prior to housing development.

2.4. Soils

The soils within the fire perimeter were mapped and identified by the Coconino National Forest Terrestrial Ecosystem Survey (TES) (USDA Forest Service, 1995). The dominant soils are classified as Mollic Eutroboralfs, loamy-skeletal, mixed, deep cobbly sandy loams (Steinke, 2010). These soils account for about 49% of all soils and are found in the ponderosa pine vegetation type. The second most common soils are Eutric Glossoboralfs, loamy-skeletal, moderately

Fig. 8. Rill systems developing on a steep slope, Schultz Fire, 2010, above the Waterline Road, Coconino National Forest, Arizona, USA. (Photo by Daniel G. Neary).

deep and deep, very stony and very bouldery sandy loams, and account for about 33% of all soils. These soils are found in the mixed conifer lifezone. Lesser amounts of Andic Cryoborolls, deep, very stony sandy and fine sandy loams, account for about 9% and are found in spruce-fir vegetation types. The remaining 9% of soils are variable. The vast majority of soils are moderately deep or deep. Less than about 5% of all soils are shallow or talus slope, are located on the steepest slopes, and have bouldery to extremely bouldery surfaces.

Water repellency of the soils was assessed by the Burned Area Emergency Response Team in 2010 immediately after the fire (BAER, 2010; Steinke, 2010). Soils on slopes <15% generally had low water repellency. These areas accounted for about 66% of the Schultz Fire area. When slopes increased to the 15 to 40% range, water repellency rose to a medium classification. This accounted for another 15% of the fire area. On slopes >40% (19% of the fire area), water repellency was initially high. This condition contributed significantly to the excessive erosion and rill and gully development which occurred during the July 20, 2010, storm.

Fig. 9. Small gully development on steep slopes above the Waterline Road after the Schultz Fire, 2010, Coconino National Forest, Arizona, USA. (Photo by Daniel G. Neary).

2.5. Photography

New rill and gully formation were assessed along the Waterline Road using visual and photographic surveys. Long-term measurements are being planned for on-the-ground measurements, terrestrial LiDAR, and repeat aerial photography. The first set of photos was taken on October, 27, 2010, at a scale of 1:12,000 by Kenney Aerial Mapping, Phoenix, Arizona. Repeat photography will be done in late September of each year to follow.

3. Results and discussion

Substantial amounts of soil were eroded out of a newly developed rill and gully system, removing the A horizon and much of the B horizon. Prior to the fire there was minimal presence of rills or gullies as the soil was protected by a thick O horizon. This protective organic layer burned off during the fire leaving the soil exposed to raindrop impact and erosion. There was widespread occurrence of high severity fire, with some watersheds classified as 70% high severity wildfire. This left most of the soils with moderate to severe water repellency, so surface runoff was extensive. Peakflows from the July 20th storm contained high concentrations of ash and topsoil material. Mineral soil loss is estimated to be >5 cm on many areas of 2000 ha of the upper watersheds.

The development of an extensive rill and gully network fundamentally changed the hydrologic response of the upper portions of every catchment (Fig. 3). Rills are self-organizing erosion systems characterized by numerous and randomly occurring small channels of only several centimeters in depth and centimeters to tens of meters long (Nearing et al., 1997). Sediment yields increase with increasing slope, rill spacing decreases as slope angle increases, rill patterns show an increased elongation and parallelism on steeper slopes, and hillslope rills tend to be evenly spaced on bare, straight slopes (Favis-Mortlock et al., 2000).

Rills on the upper slopes of the San Francisco Peaks within the Schultz Fire perimeter are now 10–20 cm deep into the B and C horizons running the entire length of slopes. Parallel rills in the right of the Fig. 8 photo demonstrate the transition from sheet erosion to rill erosion. The rills are 30 to 40 cm apart crossing entire slopes. They are up to 5 cm deep and beginning to coalesce. The rills shown in Fig. 9 are transitioning to small gullies 20 to 30 cm deep. They are cutting below the ponderosa pine surface root systems and into fragmented and weathered C horizon andesite and dacite.

The large scale of the rilling and gullying on hill slopes after the Schultz Fire is shown in Fig. 10. This slope was treated with straw mulch, but the runoff from July 20, 2010, that created the rill and gully system, stripped the mulch off soil surfaces. All the slopes of the upper watersheds where gradients are 100% or more, were eroded in a similar fashion. These rills and gullies did not exist before the Monsoon runoff started as demonstrated by post-fire and pre-runoff photos.

Small lateral gullies that are 50–100 cm deep (Fig. 11) merge into now deeply incised main drainage gullies (3–5 m deep) that occupy previous swales in the upper mountain slopes (Fig. 12). Despite the elevation and precipitation regime there are no perennial stream channels on these slopes. Flood flows in July and August of 2010 incised deeply into the slopes consisting of volcanic colluvial material and ash and tephra deposits. In many places the gullies have cut down to bedrock, thus allowing subsequent flood flows to scour out fresh, un-weathered material. The pre-fire slope surface was about 1 m above the individual on the left in Fig. 12. The deep incisions of these main drainage gullies has lowered the base level of the smaller lateral gullies, leading to additional headward cutting of the gully system, and the potential for lateral expansion.

Fig. 13 shows the exposed tree root systems along a deeply incised drainage channel below the Waterline Road (contour-following road

Fig. 10. Rill and gully system on a ridge of the San Francisco Peaks marked by straw mulch removal. (Photo courtesy of the USDA Forest Service).

along the western side of the watersheds shown in Fig. 3). The oversteep banks are future sources of sediment for the drainage channels which now convey surface runoff and sediment rapidly into the major drainages. The tree roots pose another future erosion hazard. There is a potential for mass slope failures on the steep slopes of the upper watersheds within the Schultz Fire perimeter 5 to 10 years after the fire due to decomposition of the roots. Tree roots provide much of the shear strength on forested slopes, but shear strength declines significantly after the roots decay (O'Loughlin and Pearce, 1976; Swanson, 1981).

Fig. 11. Large rill systems developing on a steep slope (right) and small gully development beginning (left). Schultz Fire, 2010, above the Waterline Road, Coconino National Forest, USA. (Photo by Daniel G. Neary).

Wildfires often produce severe watershed impacts, especially in steep terrain (DeBano et al., 1998; Neary et al., 2008). Interruption of watershed processes results in significantly increased runoff (Ice et al., 2004). The intense, short duration rainfall of the 2010 monsoon in northern Arizona interacted with slope, water repellency and extensive areas of bare soil to produce flood flows orders of magnitude in excess of flows produced by similar pre-fire rainfall events. These events eroded significant amounts of soil and led to the development of large rill and gully networks. The networks now cover much of the upper mountain. Sediment delivery to the channels is likely to taper off after 3–5 years, but could increase due and future slope failures.

Fig. 12. Deeply incised (3 m) main drainage gully within the Schultz Fire along the Waterline Road, Coconino National Forest, Arizona, USA. (Photo by Karen A. Koestner).

Fig. 13. Deeply incised drainage channel with over-steepened banks and exposed root systems, Schultz Fire 2010, Coconino National Forest, Arizona, USA. (Photo by Daniel G. Neary).

Crown-replacing wildfires like the Schultz Fire of 2010 have major impacts on the forest ecosystem, basin hydrology, and the people that inhabit the region. Research will continue on the Schultz Fire for many years to document changes in the landscape and post-fire ecosystem recovery.

4. Conclusions

The Schultz Wildfire of 2010 in north central Arizona produced the conditions for a “perfect storm” of flooding and erosion. Due to high winds, high fuel accumulations, and low humidity, the fire burned the entire eastern face of the San Francisco Peaks. Over 40% of the landscape area was classified as high severity fire, and in some watersheds fire severity exceeded 70%. Heavy rainfall within a month of the fire caused unprecedented rill and gully erosion due to the lack of a forest floor organic mat, water repellent conditions, and steep slopes. Rainfall quickly eroded much of the soil A horizon and parts of the B horizon, creating an unprecedented and extensive rill and gully network that extended from drainage bottoms to ridgelines. This network fundamentally altered the hydrologic regime of the upper watersheds, routing water into major drainage channels more efficiently and in shorter time periods. The change in the hydrologic network increased the volume of water transported off the mountain, the numbers and sizes of debris flows, and the total amounts of sediment delivered to human developments on an alluvial fan at the base of the mountain. Slopes in the upper watersheds were too steep (60 to 100%) to allow any successful mitigation actions. This type of natural event occurs on a time-scale of thousands of years. The only successful mitigation would have been to prohibit development of the alluvial fan.

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