A 12-YEAR, POST-WILDFIRE GEOMORPHOLOGIC EVALUATION OF ELLISON CREEK, CENTRAL ARIZONA

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Our knowledge of the effects of fire on riparian ecosystems in the Southwest is limited. Most fire studies have focused on upland forest habitats for a variety of reasons. Although fire is a common and natural disturbance that affects riparian ecosystems, the increasing occurrence of high-intensity fires has had detrimental effects on the composition and structure of riparian ecosystems (DeBano et al. 1998; Ellis 2001; Medina and Martin 1988; Johnson et al. 2000). Wildfires and prescribed burns can affect riparian systems both directly and indirectly (DeBano and Neary 1996). The direct effects of fire on vegetation and soil often results in increased runoff and induced erosion of the uplands, with subsequent flooding and scouring of the riparian zone. Huang and Nanson (1997) reported that removal of riparian vegetation can cause channels to vary their width by more than five times. Accumulations of fallen trees and other woody debris can further affect channel morphology, streamflow, and sedimentation and deposition processes (Smith and Fischer 1997). Fire acts upon forest soils to produce a hydrophobic soil layer that reduces infiltration and increases runoff to stream channels (Medina and Martin 1988).

The indirect effects of fire in riparian areas can include increased stream temperatures, the alteration of organic matter input to streams, increased peakflows and sediment yields, debris flows, and population changes in aquatic fauna. In general, wildfire decreases the stability of the watershed such that erosional events cause major changes to the geomorphology of the riparian zone. Physical changes are often evident for several decades, unlike vegetation and other biological components, which can recover quickly. Channel form and stability are integral factors in the structure of riparian systems. Characteristics related to channel cross-sectional form influence channel shape and ultimately the overall function and quality of the habitat (Olson-Rutz and Marlow 1992). In short, fire causes a disequilibrium in the hydrologic regime and acts upon the channel to produce geomorphic instabilities in response to rainfall, sediment loads, and changes in gradient and substrates.

In June of 1990, lightning set off a wildfire that burned 11,000 ha of ponderosa pine–juniper/oak woodland below the Mogollon Rim on the Tonto National Forest of central Arizona (Figure 1). The fire known as the Dude Fire was then considered the largest and worst wildfire in Arizona history. The fire burned across the headwater region of several watersheds, including Dude Creek, Bonita Creek, Perley Creek, Ellison Creek, and Tonto Creek. With the arrival of summer monsoons 2 weeks later, overland flow produced flood flows laden with ash and debris. Sediment samplers in Bonita Creek, an adjacent watershed in the burn area, measured high concentrations of ash and fine particulates (700 g/L) in a slurry-like consistency in the initial flows (Medina, unpublished data). Ensuing thunderstorms produced increasingly larger flood flows throughout the summer, which initiated severe channel degradation.

Herein, we document geomorphologic changes that occurred on Ellison Creek, a first-order stream, between June 1990 and June 2001. Cross-channel geomorphology transects were installed immediately after the fire to document changes in channel profile over time. Transects were read in 1990, 1992, 1996, and 2001. Permanent cross-sectional transects and methodologies were used to measure and evaluate channel form and its response to both natural and human-induced disturbances (Olson-Rutz and Marlow 1992; Platts and Nelson 1985). Due to the variability found within riparian ecosystems, repeatable procedures and measurements are essential in evaluating stream channel alterations and the overall spatial and temporal functioning unique to these systems (Platts and Nelson 1985).

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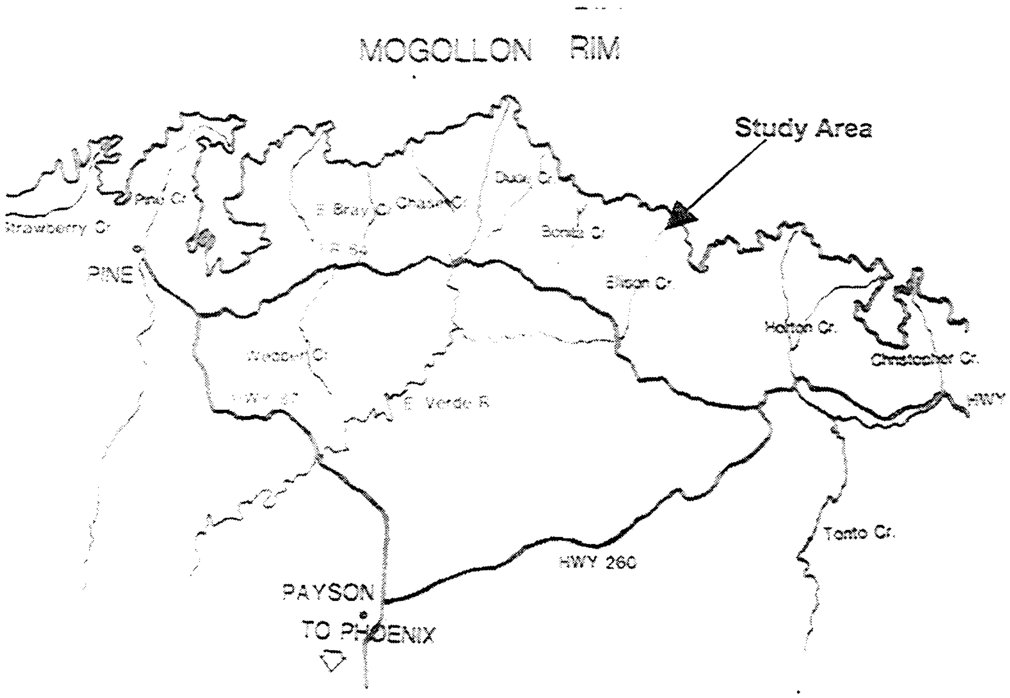

Figure 1. Location of Ellison Creek and associated streams of the Dude Fire study area.

STUDY SITE

The study area is in central Arizona immediately below the Mogollon Rim in the Tonto National Forest (Figure 1). Elevations range from 2350 m in the upper headwaters where ponderosa pine (*Pinus ponderosa*) predominates, to 1450 m in the pinyon-juniper-oak zone. Precipitation is bimodal with summer monsoons and winter rainfall and snows. The average annual precipitation for the area is 635 mm. Temperature ranges from –10° C to 32° C with average annual temperatures of 14° C (Medina 1990). The geology of the study area is a complex lithology of sandstones in the higher elevations and on ridgetops, and highly dissected Redwall limestone beneath (Parker and Flynn 2000). Flow emanates from springs in the Coconino Sandstone or Lower Supai Formations. This perennial flow persists over the Lower Supai and Naco Formations, dissipating when contact is made with the Redwall Limestone. Riparian soils are mostly lithic psammaquents, with diverse soil complexes formed in areas of direct contact with calcareous upland soils. Sandstone-derived soils are uncohesive and highly erosional, in contrast to the clayey and cohesive soils derived from siltstone-mudstone matrices of the Supai, Naco, and Redwall Limestone Formations.

Riparian vegetation is characterized by scattered stands of Arizona alder (*Alnus oblongifolia*), Arizona sycamore (*Platanus wrightii*), and Arizona walnut (*Juglans major*), with scattered clones of New Mexico raspberry (*Rubus neomexicanus*), black cherry (*Prunus serotina*), and occasional willow (*Salix* spp.) as the principal shrubs. Kentucky bluegrass (*Poa pratensis*) was the dominant streambank vegetation. Key obligate wetland graminoids such as sedges (*Carex* spp.) and rushes (*Juncus* spp.) are rare. The thin riparian corridor is largely canopied by mixed conifer species and ponderosa pine.

The Forest Service engaged in several post-fire rehabilitation actions, including removal of downed woody debris in main channels, building debris catchers and sediment traps, and reseeding. Debris removal is a common post-fire precaution undertaken to prevent debris jams from forming during floods, which when breached can send torrent flows downstream that severely impact rural communities, roads, and utilities. The burned area was reseeded with weeping lovegrass (*Eragrostis curvula*) twice, because the seed of the first sowing was washed away by the first summer storms. Riparian corridors were reseeded with forage mixtures of orchardgrass (*Dactylis glomerata*), bromes (*Bromus* spp.), and wheatgrasses (*Agropyron* spp.).

METHODS

Two study sites (1 and 2) were established and photographed immediately after the fire in June of 1990. An additional site (3) was established in 1996. Permanent cross-channel transects have been established at each site. Sites 1 and 2 were assessed in 1990, 1992, 1996, and 2001, and site 3 was assessed in 1996 and 2001. Transects were placed across the stream channel perpendicular to the flow of the water. Permanent stakes were marked and leveled to facilitate repeated measurements. Initial measurements in 1990 and 1992 were made using the sag-tape method, and subsequent measurements were made using a laser level. Beginning at the right bank transect stake, vertical distances from the level line to the contact with channel slope or bottom were measured at half-meter increments across the channel. Each transect was photographed to document visual changes.

Channel cross-sectional area and shape (GINI coefficient) were determined by comparing channel profiles for respective transects between years using Winxspro (Fischer 1998). Changes in cross-sectional areas were compared between the different years to quantify the net change in channel geomorphology. The calculated area has a positive value if the area of the second cross section is greater than the area of the first. Conversely, a negative value results if the area of the second cross section is less than the area of the first.

The GINI (G) coefficient is a mathematical index adapted from economics and plant population biology that describes the distribution of channel depth measurements (Olson-Rutz and Marlow 1992). The direction and magnitude of change in G coefficients for a cross section over time describes the change in channel shape. The Gini coefficient (G) is the arithmetic average of the differences between all pairs of depths (Y_i - Y_j):

$$G = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} \left| Y_i - Y_j \right|}{2n^2 \, Y_{avg}}$$

An increase in the G coefficient (> 0 and < 1) indicates that the channel is becoming deeper and narrower. Conversely, a decrease in G (< 0) indicates that the channel is becoming flatter and wider. The net difference between G values for respective profiles is expressed as G_{DIFF}. Changes in cross-section shape can affect hydraulic and geomorphic processes, which can influence various biological components (e.g. stream biota, vegetation). Change-in-area indices do not always describe channel form. The G coefficient is a repeatable index that quantifies stream channel form independent of cross-sectional area.

To quantify changes in cross-sectional area, the net percent change ($\Delta A\%$) between the years of study was calculated for each transect. Changes in channel geomorphology are dynamic in that cross-sectional areas increase with degradation and decrease with aggradation. Hence, the absolute net percent change $|(\Delta A\%)|$ was also calculated for each transect to portray the magnitude of change (Olson-Rutz and Marlow 1992).

$$\Delta A\% = \frac{\sum_{i=1}^{n} \left(Y_i \text{ before} - Y_i \text{ after} \right)}{\sum_{i=1}^{n} Y_i \text{ before}}$$

$$\left| (\Delta A\%) \right| = \frac{\sum_{i=1}^{n} \left| \left(Y_i \text{ before} - Y_i \text{ after} \right) \right|}{\sum_{i=1}^{n} Y_i \text{ before}}$$

RESULTS

Major changes in cross-sectional areas were observed between 1990 and 1992 (Table 1), or the immediate post-fire period. Cross-channel profiles (Figures 2 and 3) illustrate these relative changes in depth and width; differences were more pronounced on site 1 than other sites. There was a negative change in cross-sectional area of 42 percent on site 1 and 36 percent on site 2 between 1990 and 1992. This equates to an area change in the channel of 10 m^2 and 4.6 m^2, respectively. Differences in cross-sectional areas for the same sites between 1992 and 1996 were also negative, ranging between 12 and 6 percent with area changes of 2.7 m^2 and 2.1 m^2, respectively. The period between 1996 and 2001 was marked with variable occurrences of aggradation and degradation with relatively little net change (Table 1). Differences in cross-sectional areas ranged between –7 percent at site 1 and 1.1 percent at site 2, with area changes of 2 m^2 and near 0 m^2, respectively.

The differences between absolute net change ($|(\Delta A\%)|$) and net change ($\Delta A\%$) indicate that channels are experiencing some degree of aggradation and degradation that varies spatially and temporally between sites (Table 1 and Figures 2, 3,

Table 1. Cross-sectional areas (m^2), GINI coefficients, and change in area (%) between years for respective study sites on Ellison Creek. Coefficients G1 and G2 are determined for respective years noted in period.

Site	Period	Area	G 1	G 2	G_{DIFF}	ΔA%	|(ΔA%)|
1	1990 vs. 1992	10.0	-0.349	-0.306	0.043	-42.1	42.1
	1990 vs. 1996	12.1	-0.349	-0.301	0.048	-51.2	51.2
	1990 vs. 2001	12.2	-0.349	-0.319	0.030	-51.8	51.8
	1992 vs. 1996	2.1	-0.306	-0.301	0.005	-6.4	6.4
	1992 vs. 2001	2.2	-0.306	-0.319	-0.013	-6.8	6.8
	1996 vs. 2001	0.1	-0.301	-0.319	-0.018	-0.4	0.4
2	1990 vs. 1992	4.6	-0.327	-0.416	-0.088	-35.9	35.6
	1990 vs. 1996	7.2	-0.327	-0.369	-0.042	-54.3	55.4
	1990 vs. 2001	7.3	-0.327	-0.374	-0.047	-47.7	48.5
	1992 vs. 1996	2.7	-0.416	-0.369	0.046	-11.7	11.8
	1992 vs. 2001	2.7	-0.416	-0.374	0.041	-10.8	10.9
	1996 vs. 2001	0	-0.369	-0.374	-0.005	1.1	1.1
3	1996 vs. 2001	2.0	-0.362	-0.325	0.037	-7.1	7.2

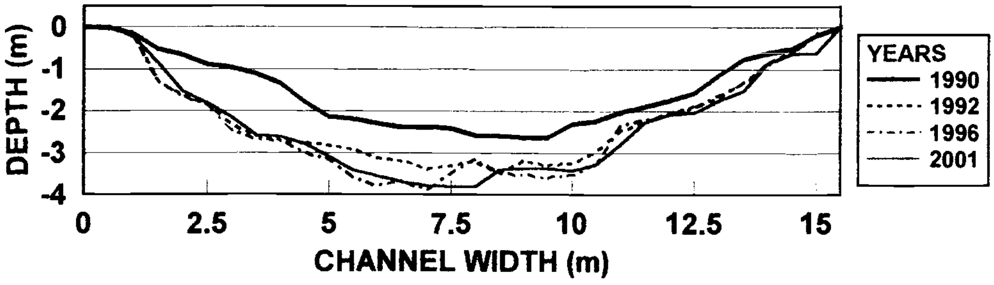

Figure 2. Cross-channel profiles across time for Ellison Creek site 1.

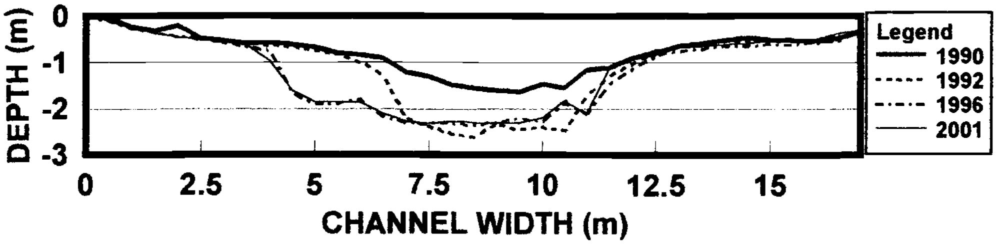

Figure 3. Cross-channel profiles across time for Ellison Creek site 2.

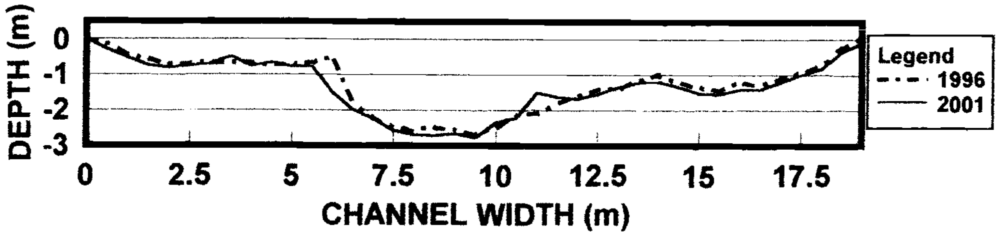

Figure 4. Cross-channel profiles across time for Ellison Creek site 3.

and 4). Minor differences were detected in the lowermost sites 2 and 3, and no differences were observed in the uppermost site 1.

Differences in channel shape were most evident on sites 1 and 2 between 1990 and 1992 (Figures 2 and 3). The differences between years in the G coefficients were mixed across years and sites. Examination of the profiles across time and sites reveals a general pattern of channel incision and channel widening immediately after fire (Figures 2 and 3). The later years reveal a mixed pattern of deepening and widening, suggestive of a possible trend toward quasi-equilibrium. The G_{DIFF} values on site 1 were positive between 1990 and all subsequent years, indicating a trend toward a deeper and narrower channel (Figure 2). Similarly, the G_{DIFF} value on site 3 was positive between 1996 and 2001 (Figure 4). Conversely, G_{DIFF} values on site 2 were negative between 1990 and all subsequent years, indicating a trend toward a shallower and flatter channel, with some aggradation in 2001 compared to 1996 (Figure 3). The net difference in G_{DIFF} values across all sites is 0.037, which indicates a general trend toward a deeper and narrower channel along the creek.

DISCUSSION

The major changes in channel geomorphology are an expected post-fire response considering that the dynamic equilibrium of upper Ellison Creek watershed was altered as a result of the wildfire. Photographs taken during three typical summer storms in July of 1990 evidenced the widespread overland flow, high runoff, and flooding conditions that exceeded the 2–3 m high terraces in many locations, spreading floodwaters onto the forest floor. Woody debris jams exacerbated channel scouring by breaking and releasing dammed-up water with increasing magnitude progressively downstream. The energy of floodwater and the physical impact of large boulders and other channel materials excavating the channel resulted in major geomorphologic change within the creek. These changes further manifested into major changes in streamside and terrace vegetation on some segments. Some stream segments are laden with large woody debris, and others are scoured free of debris and small cobble-rock substrates.

Cross-sectional data and profiles confirm photographic and observational data of the erosional processes that occurred after the fire. The additional discharge from overland flow caused initial channel incision in the sandy substrates down to bedrock, which was about 1–1.5 m below the initial channel surface. The incision phase was followed by channel widening in response to the higher than normal peakflows during the first 2 years, followed by a transitional period (1992–1996) during which the channel adjusted to new gradients, channel form, and channel materials. The G_{DIFF} values of each site changed over time, confirming these dynamics.

In mountain streams, riparian forest dynamics are primarily controlled by the physical disturbance of vegetation and geomorphologic processes (Johnson et al. 2000). The long-term consequences on riparian zone dynamics are barely evident and are largely obscured by many other factors. Large volumes of woody debris from fallen trees are presently influencing in-channel equilibrium dynamics on Ellison Creek. Channel substrates are very coarse and little soil is available for streambank and floodplain development. The influx of fine sediment (< 2 mm) from upland sources is limited, probably owing to the dense monoculture stands of weeping lovegrass that were established from reseeding. The reseeded species in the riparian corridor are largely absent and have been replaced with a variety of forbs. New Mexico locust (*Robinia neomexicana*) stands are common within the floodplain; they act to retain large woody debris, which has caused additional lateral erosion of in-channel materials and terraces. All of these interactions in changes in water levels and streambank conditions will have a long-term effect on the vegetative community. Medina and Martin (1988) noted that vegetative and channel changes can continue beyond 38+ years following a wildfire. The lack of fine sediments in the channel is likely to inhibit the development of a stable floodplain and streambanks for several decades.

Spatial and temporal differences in the statistical results suggest that multiple processes are operating in response to the fire and the subsequent flood events. The degree of variability found within the results for all four parameters is a product of the ecosystem's adjustment process fluctuating between transects and among the various years of study. Such variability is a common characteristic of riparian ecosystems (Johnson et al. 2000). The sensitivity of the indices tested can be used to quantify the changes in cross-sectional form over time (Olson-Rutz and Marlow 1992). The increases in depth and channel width and percent change, observed in all plots, are commonly the result of hydrologic adjustments to storm events. Differences over time within the individual transects provide estimates of channel adjustment that are unique in both space and time.

RESEARCH AND MANAGEMENT IMPLICATIONS

As policy and socioeconomic views on fire and their natural and necessary roles in ecosystems change, it becomes increasingly important to study and understand the parameters that act to regulate the functions and processes of riparian ecosystems. Riparian habitats are highly variable and the effects of fire can cause multiple outcomes within and between streams. A comprehensive understanding of how fire affects the structure and function of riparian systems is necessary to introduce policies that will restore unhealthy forests and reduce the risks and impacts of fire in the future (Moreno and Oechel 1994). Furthermore, a clearer understanding of the post-fire effects on the redevelopment of terrestrial and aquatic components is essential for developing rehabilitation plans. The role of fire in the Southwest's riparian ecosystems is poorly understood and is often generalized from other regions.

ACKNOWLEDGMENTS

A special thanks to Shawn Kelley, Jackson Leonard, and Paola Gutierrez for their technical assistance.

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