

Post-Wildfire Sedimentation in Desert Mountain Streams and Effects on Lowland Leopard Frog Habitat, Saguaro National Park

By John T.C. Parker and Don E. Swann

Abstract

Post-wildfire sedimentation in the Rincon Mountains of Saguaro National Park overwhelms the sediment transport capacity of small desert streams and buries bedrock pools, known as tinajas, that serve as habitat for the lowland leopard frog, a declining species in southeastern Arizona. An increase in the frequency of large, severe, crown fires because of fire-suppression practices in the late 19th and 20th century, as well as fragmentation of leopard frog habitat resulting primarily from human activities, presents leopard frog populations with disturbances of unprecedented frequency and magnitude. Tree-ring studies show that large, severe wildfires were rare, extreme events in the Rincon Mountains before the middle of the 20th century. From 1989 through 2003, however, Saguaro National Park has been the site of five severe wildfires and post-wildfire sedimentation from such events has filled bedrock pools and destroyed leopard frog habitat in most stream channels within the study area. Persistence of wildfire-induced sediment deposits in bedrock pools has resulted in longer recovery periods for aquatic habitats in the Rincon Mountains than reported

for similarly affected habitats in perennial stream channels in wetter environments. In Loma Verde Wash, all tinajas that provided leopard frog habitat were buried within three years after the 1999 Box Canyon fire and remained so as of summer 2007. The degree to which other stream channels were affected by post-wildfire sedimentation has not been well documented, but the near absence of leopard frogs in Wildhorse Canyon in the late 1990s, followed by increasing populations in subsequent years and high volumes of sediment remaining in some tinajas, suggests a similar history as a result of the 1989 Chiva fire. Low populations of frogs in Madrona Canyon and Rincon Creek may be indicative of wildfire effects following the 1994 Rincon fire. The most recent severe wildfire, the 2003 Helens II fire, resulted in high volumes of sediment delivery from hillslopes to headwaters of Joaquin Canyon. Although evidence of watershed recovery was observed two years after the Helens II fire, a slug of sediment moved downstream episodically and had buried at least one large tinaja outside park boundaries by October 2005. Chimenea Creek, the only major stream channel to escape significant impact from severe wildfires in recent decades, contained the largest and healthiest leopard frog population as of summer 2007. About 40 percent of the watershed above Chimenea Creek was burned by prescribed fires and managed wildfires since 1994. The condition of Chimenea Creek suggests that fire-management policies that include prescribed fires and management of small, naturally caused wildfires might offer protection for leopard frog populations in Saguaro National Park from excessive sedimentation and destruction of habitat.

Introduction

The Rincon Mountain District of Saguaro National Park in southeastern Arizona contains some of the last remaining habitat in the Tucson Basin for the lowland leopard frog (*Rana yavapaiensis*), a species that was once common throughout the basin. Habitat loss resulting from urbanization and exploitation of water resources has pushed the leopard frogs to the fringes of the

basin where they now occupy small numbers of bedrock pools (known in the southwestern United States as *tinajas*) in the canyons of adjacent mountain ranges. The desert mountains in which the frogs reside are subject to a variety of hazards including drought, fire, and flash floods, all of which are processes that have operated for millennia and to which the frogs have presumably adapted. In the past two decades, however, the park has had four large, severe crown fires and one desert fire, events that were uncommon under prehistoric conditions. At least three and perhaps all of those fires have caused catastrophic sedimentation, filling tinajas with sand and gravel and destroying them as frog habitat. These events appear to be unprecedented in frequency, if not magnitude, and represent a threat to the continued existence of the lowland leopard frog in the park. The management issues facing the National Park Service include protection of leopard frog habitat and development of fire-management policies that will produce a more natural fire regime without presenting an additional threat to park resources. To develop effective strategies, it is important that park managers understand the fire history and ecology of the Rincon Mountains, the physical processes that operate on watersheds and stream channels before and after fires, the relationships between those processes and aquatic habitats, and the processes of watershed and stream-channel recovery from disturbances.

All aquatic organisms that inhabit running waters are subject to disturbance as a result of abrupt changes in stream discharge, varying influxes of sediment, nutrients, contaminants and the instability of channel substrate (Meyer and others, 1988; Resh and others, 1988; Giller and Malmqvist, 1998; Cushing and Allan, 2001). The variables of stream discharge, water quality, and channel morphology are dependent on climatic conditions, hydrogeologic properties, and human activities that may vary greatly over time and space. Wildfires change watershed characteristics, such as vegetation cover and soil properties, in ways that can produce abrupt changes in hydrologic

and geomorphic processes with a consequent change in aquatic ecosystems. Interest in the effects of wildfire on aquatic habitats is relatively new and has focused primarily on macroinvertebrate communities as well as chemical and nutrient changes (Minshall, 2003). The effects of wildfire on vertebrate populations have been studied less extensively, and most studies have focused on fish (Lamberti and others, 1991; Rinne, 1996; Howell, 2006). Pilliod and others (2003) summarized peer-reviewed research into wildfire effects on amphibian populations. Of the 12 North American studies included in the summary, only one examined population changes in a stream environment (Gamradt and Kats, 1997); the authors of the rest of the studies looked at terrestrial amphibian populations. There has been no published research on wildfire effects on amphibians in the intermittent streams typical of the desert Southwest.

Desert-mountain streams are particularly harsh environments for aquatic life (Fisher, 1986; Giller and Malmqvist, 1998). Flow regime, a principal control on the distribution of aquatic life (Bunn and Arthington, 2002), is characterized by extreme variability ranging from many weeks of zero discharge to flash floods with peak discharges up to six orders of magnitude above average stream discharge (Baker, 1977). Desert streams are also characterized by discontinuity and poor integration of drainage systems, resulting in fragmentation of aquatic habitat (Cushing and Allan, 2001). Despite the particular severity of conditions in desert mountain streams, studies of flood disturbance of aquatic environments in Sycamore Creek, a mainly intermittent stream in central Arizona, have shown that macroinvertebrate and periphyton communities can return quickly to pre-flood levels (Gray, 1981; Gray and Fisher, 1981; Fisher and others, 1982; Grimm and Fisher, 1989; Boulton and others, 1992). In addition to the extremes of the hydrologic system, desert mountains in the southwestern United States are subject to frequent natural fires. Fire suppression practices in the late 19th through the 20th century have led to particularly large and destructive crown fires that

may have geomorphic consequences far more severe than those with which aquatic organisms have had to cope in the past (Baisan and Swetman, 1990; Parsons and Botti, 1996).

In this paper we present an example of extreme biotic disturbance, namely the burial of breeding and feeding habitat for the lowland leopard frog in the Rincon Mountains following large stand-replacing wildfires. This level of disturbance is unusual in the nearly total destruction of habitat within watersheds and the long post-wildfire recovery periods. We describe (1) the mechanisms that produce the disturbance and the relation of excessive sedimentation to the wildfire history of the study area; (2) watershed recovery and persistence of disturbance in stream channels; (3) describe the effect of post-wildfire sedimentation on lowland leopard frog populations; (4) discuss the potential for recovery of those populations that have been affected by post-wildfire sedimentation; (5) discuss the prospect for future disturbances and the management options available for attempting to protect park resources. This paper is based upon findings in an investigation of post-wildfire sedimentation conducted 2004-2006 by the USGS in cooperation with Saguaro National Park; descriptions of the data and the methods of data acquisition and analysis are presented by Parker (2006).

Description of Study Area

The Rincon Mountain District of Saguaro National Park encompasses 272 km² of rugged upland desert and mountainous terrain east of Tucson. Elevation ranges from about 760 m along the western edge of the park to about 2,600 m on Mica Mountain and Rincon Peak in the Rincon Mountains (Figure 1). The park is mostly mountainous, but the most heavily visited areas are the bajadas, the rolling land surface of ridges and valleys formed by overlapping alluvial fans, along the base of the mountains at elevations between about 760 and 975 m.

The climate is semiarid with summer and winter rainy seasons. Average annual precipitation is about 300 mm near the base of the mountains and about 760 mm at the highest elevations (Bowers and McLaughlin, 1987). During the summer monsoon season, convective thunderstorms typically produce intense, short-lived periods of precipitation with a high degree of spatial variability. Winter precipitation occurs as a result of regional frontal storms in which rainfall generally is less intense, but can last for several hours to several days. Snowfall is common above 2,100 m in the winter (Bowers and McLaughlin, 1987).

The predominant rock types of the Rincon Mountains are Precambrian granodiorite and quartz monzonite that have intruded into older metasedimentary rocks. Deformation of the rocks ranges from kilometer-scale fracturing to outcrop-scale foliation and folding. The rocks typically weather to coarse, gravelly sand that covers most hillslopes, although steep slopes of exposed bedrock are common.

Vegetation includes Sonoran Desert scrubland, which includes extensive stands of saguaro cactus (*Carnegiea gigantea*) and other cacti as well as various yucca species and woody shrubs that blanket the bajadas and lower mountain slopes. With increasing elevation, the hillslopes are vegetated with grassland and scrubland, oak–juniper woodlands, juniper and piñon pine woodlands, ponderosa pine forest, and mixed conifer forest (Bowers and McLaughlin, 1987).

Stream-channel positions within the study area generally are bedrock controlled, and the variability of channel geometry primarily depends on the geologic structure and lithology of the terrain over which the stream flows. Channels are typically narrow (5–15 m) and steep with watershed relief ratios ranging from 0.121 to 0.221. Headwater elevations range from 1,425 m to 2,640 m. Generally, little sediment is stored in the channels, and flood-plain and alluvial-terrace deposits are small and sparse.

The bedrock pools, or tinajas, within the channels exhibit a variety of morphologies ranging from nearly circular to linear and angular to irregular in plan view with depths from 0.5 to 3 m and dimensions of 1–10 m along the maximum axis. Tinajas can be formed from ponding of water behind flow obstructions, including bedrock outcrops, sills, and boulders; from plucking of rock fragments and blocks from jointed and fractured bedrock channels, and from abrasion by sand and gravel in suspended sediment, as well as by chemical erosion (Wohl, 1998; Whipple and others, 2000). A tinaja may be the product of one or all of these processes.

Most tinajas unaffected by recent post-wildfire sedimentation have little sediment on the pool bottom. A veneer of sand and gravel over a base of cobbles occurs in some tinajas, and others have only a light layer of silt and organic ooze; however, commonly one tinaja in a chain of pools is nearly filled with sandy gravel and the others contain little or no such sediment. Some pools have alluvial banks and a thicker layer of sediment on the bottom than is typical of most tinajas. In a survey of surface-water resources in Saguaro National Park, Macleod and others (2003) identified 75 perennial tinajas; however, a severe multiyear drought through the winter of 2006 had produced possibly the driest conditions in the park since the 1950s, and a number of tinajas were reported dry for the first time since at least 1996 when systematic monitoring began (Parker, 2006). Perennial tinajas are probably fed through bedrock fractures by ground-water sources; however, no investigation has been conducted to verify those water sources.

The Lowland Leopard Frog

The lowland leopard frog occupies aquatic environments in desert scrub to juniper-piñon woodlands in the southwestern United States and northern Mexico. Once abundant in much of its range, its population is now declining in southeastern Arizona, and the leopard frog has been

extirpated from its range in southwestern Arizona and southeastern California (Sredl, 2005). This population decline has led to designation of the lowland leopard frog as a Priority Vulnerable Species in the Sonoran Desert Conservation Plan implemented by Pima County, Arizona and as a Species of Special Concern by the Arizona Game and Fish Department (Arizona Fish and Game Department, 2006). The lowland leopard frog also was selected an indicators of ecosystem health for Saguaro National Park (Pima County, 2006).

Habitat of lowland leopard frogs includes perennial streams or perennial pools in intermittent streams, wetlands, and springs, as well as artificial environments such as earthen stock tanks, irrigation canals, and backyard ponds. The frogs inhabit both shallow- and deep-water habitats, the former offering emergent and perimeter vegetation for basking, and the latter offering refuge from predators and possibly hibernation sites in undercut banks and root masses (Platz and Frost, 1984; Arizona Game and Fish Department, 2006). Adult frogs may survive periods of habitat desiccation by retreating into mud cracks, rock fractures, or burrows of other animals (Howland and others, 1997). Fragmentation of lowland leopard frog habitat is probably a significant cause of population declines, including extirpation from some areas without subsequent recolonization (Sredl and Saylor, 1998).

Episodes of mass mortality of leopard frogs have been recorded in Arizona. In a 2-year study of a lowland leopard frog population occupying several pools below springs in east central Arizona, Sredl and others (1997) observed up to 90-percent mortality as a result of large floods and a subsequent fungal infection. Coeval habitat loss due to siltation of several pools may have contributed to the subsequent slow recovery of the population.

In Saguaro National Park, the tinajas that provide lowland leopard frog habitat are in first- to third-order stream channels at elevations between 850 and 1,800 m in the Rincon Mountains

(Figure 1). Lowland leopard frog individuals or populations have been observed by park staff in at least 265 tinajas; leopard frog tadpoles or eggs, which signify a possible breeding population, have been seen in 110 tinajas since systematic monitoring began in 1996.

Fire History and Management

Tree-ring studies of fire history in the Rincon Mountains show that fire was a frequent and widespread phenomenon from 1657 to 1893 (Baisan and Swetman, 1990). Surface fires, generally between 200 and 3,000 ha in extent, burned the understory of ponderosa and mixed-conifer forests at intervals of 1–13 years in the vicinity of Mica Mountain. Mean fire interval was 6.1 years. During this period, fires ignited by lightning in May and June could burn for several months before being extinguished by summer rains. Large, severe, crown fires apparently were rare before the middle of the 20th century although Baisan and Swetman (1990) cite evidence of at least one such fire of unknown age below Rincon Peak (Figure 1).

Fire frequency declined in the late 19th and into the 20th century in the Rincon Mountains and throughout the Southwest as a result of fire-suppression practices and livestock grazing that removed the forest understory (Baisan and Swetman, 1990). Except for large fires of 2,444 ha and 2,338 ha in 1943 and 1954, respectively, park records show only 409 ha burned from 1943 to 1988. From 1989 through 2003, five wildfires burned a total of 17,400 ha, more than three times the total area of all other fires combined from 1943 through 2003 (Figure 2).

Fires have burned through nearly 40 percent of the park's forests, grasslands and scrublands since 1989, involving about 50 percent of the forested areas and 35 percent of chaparral and desert scrublands and grasslands (Parker, 2006). The only substantial areas of forested watershed that have not been burned by unmanaged wildfire in the past 60 years include the Chimenea Creek

watershed, except near the watershed divide; the western part of Madrona Canyon; and the eastern to southeastern Rincon Creek watershed (Figure 1). About 40 percent of Chimenea Creek watershed has been burned in recent years, but almost all of that burned area was from prescribed fires or managed wildfires, which are naturally caused fires that are monitored and allowed to burn as long as property, human lives, and park resources are not threatened.

The spate of large, crown fires beginning in 1989 is most likely the consequence of fire suppression conducted by the National Park Service, a practice common to all other federal lands agencies beginning in the 1920s. On public lands throughout the western United States, high fuel accumulations and tree densities increased the risk of catastrophic fires and changed the distribution of fire-dependent vegetation (Parsons and Botti, 1996; Saguaro National Park, 2004). In 1968, the National Park Service changed its policy of suppressing all fires within its jurisdiction. Some fires were allowed to burn if they would contribute to the success of resource-management objectives without threatening developed areas or cultural sites. Fire managers in Saguaro National Park have employed prescribed burns since 1985 to prevent encroachment of woody vegetation into meadows, to reduce fuel loads, and to restore grasslands (Saguaro National Park, 2004).

Fire, Hydrology and Geomorphic Processes in the Rincon Mountains

Large, crown fires cause hydrologic changes that greatly amplify runoff and lower erosion thresholds, thus producing large increases in the rate of sediment delivery to channels. Increases in storm runoff of 30–400 percent are typical following such fires, and increases in peak discharges as high as 870-fold have been reported (Moody and Martin, 2001). The increase in runoff that results

from the loss of storage in the forest and scrub canopy and leaf litter can result in extreme increases in sediment load ranging from 4-fold to 220-fold (Martin and Moody, 2001; Veenhuis, 2002; Paige and others, 2003) and produce catastrophic debris flows (Cannon and others, 1998).

Under normal supply-limited processes in mountain streams, most channel-bottom sand and fine gravel is moved through the system within a few seasons, and little sediment resides in storage in the channel bottom. Increased sediment from burned watersheds can result in excessive deposition of fresh sediment in stream channels that overwhelms the stream's transport capacity and results in significant change to channel morphology and hydraulic characteristics (Moody, 2001). The amount of time the sediment remains stored in the channels depends on the volume of sediment available on hillslopes for transport, the period of time that is required for the conditions to stabilize on hillslopes, the frequency and size of streamflows available for scouring the sediment from the channel, and the physical characteristics of stream channels that govern the velocity of flows through a particular channel reach.

In July 2003, three months before the inception of this project, the Helens II fire, a hot, runaway wildfire caused by lightning, swept through the ponderosa pine and mixed-conifer forests in the Mica Mountain area. Unlike the surface fires that regularly burned the understory with little damage to the forest canopy before the late 19th century, the Helens II fire was a severe, crown fire. The Helens II fire was particularly severe on the northern slope of Mica Mountain in the upper Joaquin Canyon watershed, most of which is north of the park boundary where it drains into Tanque Verde Creek (Figure 1).

Observations of post-fire conditions in the burn area were made during five field trips in March, June, and November 2004, and in July and October 2005 (Parker, 2006). All of the field

trips were reconnaissance-level surveys in which the main objective was to rapidly assess the mechanisms of sediment transport and changes that occurred during the course of the study period.

From containment of the fire on June 30, 2003, to October 2005, precipitation totals at Manning Camp, at an elevation of 2,417 m at the southern edge of the burn area, were slightly below normal. The summer immediately after the fire was the wettest period with 377 mm of precipitation falling from July 31 through October 31, 2003 (Parker, 2006). Annual precipitation totals were about 83 and 87 percent of expected values in 2004 and 2005, respectively. A total of eight storms with rainfall intensities greater than 10 mm hr^{-1} occurred during the summers of 2003–2005.

The main mechanisms of sediment erosion from hillslopes were sheetwash and rainsplash as evidenced by splays of sand and gravel, erosion pillars and poorly defined, transient channels. Rills were few, only 5–10 m long and no more than 15-cm deep, and there was some evidence of small debris flows, such as coarse, overbank deposits along headwater tributaries (Parker, 2006). The absence of deep gullies or landslide scars indicates that sediment was moved downslope mainly by surface flow rather than as a mass. This sediment-transport mechanism is characteristic of burned watersheds where the rapid delivery and accumulation of surface water to the bare ground surface and consequent increased runoff results in minimal infiltration into the soil (Wells, 1987; Cannon and others, 1998; Cannon and others, 2001). The nature of erosion from the Rincon Mountain hillslopes, namely the diffuse movement of sediment by rainsplash, sheetwash, and soil creep, made assessment of change from repeated observations difficult. These are normal hillslope processes (Selby, 1993) that were accelerated as a result of the changed hydrologic conditions immediately following a wildfire. Measurement of the magnitude of changes in hillslope erosion

resulting from wildfire-induced hydrologic change requires detailed monitoring that was beyond the scope of this study.

By July 2005, less evidence was seen of continuing erosion from hillslopes. Movement of sediment, however, was apparent in the appearance of charcoal-laden sediment in unburned forest areas and the deposition of sediment on the upslope side of tree trunks, stumps, and newly sprouted vegetation, particularly stands of bracken fern (*Pteridium aquilinum*). Surface roughness had increased on many slopes as a result of new vegetation growth and the accumulation of fallen trees and broken branches from the stands of burned forest, and slopes that were still barren typically were armored with gravelly lag. Although much of the burned area looked as raw as it had appeared in the first year after the fire, the patchy recovery of the hillslopes was clearly taking place by revegetation and exhaustion of the available supply of mobile sediment. The effects of this partial recovery on the rate and magnitude of hydrologic processes could not be measured for this study, but in other studies in Western mountain areas, runoff and sediment transport returned to pre-fire levels within 2–7 years (Bolin and Ward, 1987; Moody and Martin, 2001). During cursory surveys of older burn areas in the Rincon Mountains that had been affected by the Chiva, Box Canyon, and Rincon fires, we saw virtually no unequivocal evidence of post-wildfire hydrologic changes. Although woodlands had not reestablished in many areas—burned snags were commonly the tallest vegetation features in the landscape—ground cover appeared as dense as in unburned areas. Evidence of sheetwash erosion was sparse and could easily have occurred well after the fires. Six years had passed since the Box Canyon fire, the most recent of the fires, and the recovery of the watershed is not surprising in light of recovery times reported for other western watersheds. Because only a small fraction of the older burn areas was surveyed, especially in the Chiva and

Rincon burn areas, it is possible we overlooked evidence of continuing post-wildfire hydrologic and geomorphic effects in those areas.

Even as the watershed of Joaquin Canyon showed evidence of recovery 2 years after the Helens II fire, a slug of sediment continued to move episodically downstream, burying tinajas and destroying some leopard frog habitat in the process. Joaquin Canyon drains the northern slope of Mica Mountain, which was the most severely burned area in that fire (Figure 1). A large, probably perennial tinaja is about 3.3 km downstream of the burn area in Coronado National Forest north of the Saguaro National Park boundary. Although the tinaja was not monitored regularly, lowland leopard frogs had been observed in the pool prior to the fire. When the channel first was surveyed for this study in June 2004, the tinaja contained water to a depth of about 0.5 m, but about 1 m of black mud had been deposited along its right bank since the pool had last been observed by park staff in July 2003. In the 2.2-km reach below the tinaja the only evidence of post-wildfire sedimentation in the channel was patchy deposits of gray, fine-grained material that appeared to be nearly all ash. The generally cobbly bouldery channel bottom downstream from the tinaja contained little sand, and the lowermost tinaja showed no evidence of post-wildfire deposition. In the next survey of the channel in June 2005, the tinaja was dry and was partially filled with 0.5–1 m of gravelly sand. There was, however, still no evidence of significant sand deposition in the channel below the tinaja. In October 2005, the Joaquin Canyon channel was visited for the last time in this study, and the uppermost tinaja was observed to be completely filled with sediment. The front of the sediment slug had moved downstream about 400 m, leaving 0.10–0.50 m-thick deposits of sand on the channel bottom. Another tinaja, about 1,100 m downstream from the first tinaja, had not been significantly affected by excessive sedimentation and was still functioning as aquatic habitat; one Sonoran mud turtle and four adult lowland leopard frogs were sighted.

The pattern of deposition in Joaquin Canyon then is rapid delivery of mobile sediment in the headwater channels as a result of accelerated hillslope erosion, remobilization of this sediment during short-lived summer streamflows and moderate winter streamflows, and the discrete, episodic transport of the sediment slug downstream. The front of the sediment slug stopped at the upper tinaja and did not continue downstream until the pool was completely filled, sometime between June and October 2005. The record of tinaja-filling in Loma Verde Wash, in which tinajas were filled from upstream to downstream over a period of 2 years following the Box Canyon fire, suggests that this is a typical pattern of sedimentation in the channels of the study area.

Lowland Leopard Frog and Wildfire-Induced Disturbance

Aquatic organisms adapt to environments characterized by disturbance that occurs over a wide range of temporal and spatial scales (Resh and others, 1988; Gore and others, 1990; Reeves and others, 1995). Post-wildfire sedimentation of the magnitude seen after recent large, severe fires in the Rincon Mountains represents a level of disturbance that probably occurred on a time scale of centuries based on tree-ring derived fire histories (Baisan and Swetman, 1990). Extreme storms also may have produced infrequent episodes of catastrophic sedimentation. In July 2006, a massive, thunderstorm complex produced record precipitation in the Santa Catalina Mountains, which neighbor the Rincon Mountains on the north. Following several days of heavy rainfall, the storms of July 31 caused hundreds of hillslope failures that coalesced into catastrophic debris flows that buried streams channels in several canyons. The event was historically unprecedented in southern Arizona (Magirl and others, 2007). Similar catastrophic events may have affected prehistoric stream channels in the Rincon Mountains and other desert mountains in southeastern Arizona with consequent destruction of lowland leopard frog populations. Such events, however, would have

occurred in an environmental setting that has been tremendously altered by human activities in the past 150 years. Lowland leopard frog habitat that once existed in large streams and associated wetlands in the valley bottom has been almost entirely eliminated by human activity. Habitat has been reduced and fragmented to an extent that may prevent recovery of lowland leopard frog populations from extreme fire or storm events. An additional modern source of disturbance is the burning of non-fire-adapted Sonoran desert landscapes, such as occurred in the Chiva, Mothers Day and Box Canyon fires (Figure 1). Exotic grasses, such as red brome (*Bromos rubens*) and buffleggrass (*Pennisetum ciliare*), are believed to be a factor in increasing the frequency of fire in desert-vegetation communities (Esque and others, 2003; Esque and Schwalbe, 2006). The burning of low-elevation vegetation communities enabled fires to spread into the lower watersheds of Wildhorse Canyon, Loma Verde Wash, and Box Canyon and may have contributed to increased post-wildfire sedimentation as a result.

Destruction of lowland leopard frog habitat as a result of post-wildfire sedimentation came to the attention of park staff after the Box Canyon fire of 1999, which burned 1,381 ha, primarily of grassland, desert scrublands, and oak-juniper woodlands in the watersheds of Loma Verde Wash and Box Canyon. At the time, Loma Verde Wash contained a large, healthy population of lowland leopard frogs. Within a few months of the fire, 38 tinajas in Loma Verde Wash received the first slugs of sandy gravel that buried all of them to a depth of 1–2 m within two years (Figure 3). The tinajas remain buried as of spring 2007, nearly eight years after the fire. Since the last sighting of frogs in Loma Verde Wash three years after the fire, no frogs have been detected during regular surveys of the channel. Two tinajas were experimentally excavated in spring 2005; they remained open during the following summer, but refilled with sediment as a result of heavy monsoon rains

and streamflow in the summer of 2006. That tinajas were refilled during that period rather than scoured suggests that abundant mobile sediment was still stored in upstream channel reaches.

Subsequent to the filling of Loma Verde Wash tinajas with sand and gravel, park staff discovered at least one large tinaja in Wildhorse Canyon that had presumably filled after the Chiva fire of 1989 and showed no signs of sediment removal when last observed in September 2004. There is no record, however, of how many and during what period of time the 113 tinajas mapped in Wildhorse Canyon filled with sediment following the fire.

The effect of excessive sedimentation in the lower reaches of the stream channels is to fill the tinajas with coarse sand and fine gravel that displaces all or most of the tinaja volume available for water. The sediment also blocks or absorbs the trickle of ground-water flow entering tinajas from fractured bedrock, desiccating the tinaja and initiating a die off of riparian and emergent vegetation, such as cattails (*Typha sp.*), that serve as cover for lowland leopard frogs. Finally, the post-wildfire sedimentation destroys much of the heterogeneity of the tinajas, which typically vary among each other in the amount and type of sediment in residence in and along the margins of the pools. The degree to which frog populations are affected by such sedimentation depends on the number of tinajas that are filled within a reach and the persistence of the tinaja-fill sand deposits following their emplacement.

The absence of data on pre-wildfire conditions in most channels makes a quantitative determination of sediment storage time elusive. The sedimentation history of most channels is based mainly on indirect observations. From July 2005 to April 2006, park staff conducted surveys of 23 tinajas in 7 stream channels to measure pool dimensions and probe sediment deposits to determine depth of sedimentation and volume of the deposits (Table 1). All of the tinajas were in channels below watersheds that had burned in the past two decades, although fires in the watershed

above Chimenea Creek have been mainly prescribed burns and managed wildfires. Tinajas in Loma Verde Wash contained the highest volumes of sediment per pool volume with three of the seven pools sampled having ≥ 100 -percent of pool capacity filled with sand and gravel. The mean volume of pool capacity occupied by sediment for the Loma Verde pools was 81 percent, compared to 17.3 percent for the remaining 16 pools in other stream channels. Wildhorse Canyon was the only other channel in which a sampled tinaja was more than 50-percent filled with sediment. The only other tinajas that were surveyed and had significant sediment fill are those in Madrona Canyon, downstream from the 1994 Rincon fire (Parker, 2006).

Chimenea Creek is the only major drainage basin in the Rincon Mountains that has not been significantly burned by an uncontrolled crown fire in the past two decades. The volume of sediment in the four tinajas in Chimenea Creek that were surveyed ranges from zero to 20 percent, and visual surveys in spring 2007 of the other 20 tinajas with a record of lowland leopard frog populations indicated a similar range of sediment volume. The recent fire history of the Chimenea Creek drainage basin probably most closely approximates the natural pre-suppression fire regime within the study area, and the degree of sedimentation in tinajas is probably representative of normal background sedimentation levels.

Observations of leopard frog populations may give some indication of the post-wildfire sedimentation history in stream channels, although a number of factors can affect population counts and interpreting the sedimentation history from these data is problematic (Parker, 2006). Saguaro National Park staff has been monitoring leopard frogs since 1996 on a regular annual or seasonal basis. There is no question that frog populations in canyons downstream from severely burned areas have been affected by these fires, most likely from excess sedimentation (Figure 4). No frogs were observed in Wildhorse Canyon tinajas during surveys in 1996, but a few individual frogs were

observed in 1998; since that time, there has been a substantial increase in the number of frogs and the number of tinajas supporting frog populations.

The effect of post-wildfire sedimentation on leopard frog populations in other drainages generally has not been as well documented as in Loma Verde Wash and Wildhorse Canyon (Saguaro National Park, unpublished data). Historically, Box Canyon contained leopard frog habitat. No frogs have been observed in that channel since the Box Canyon fire, but populations had declined before the fire. Frog populations have fluctuated in tributaries of Rincon Creek, including Madrona Canyon, but have persisted in small numbers. The extent to which those populations were affected by the 1994 Rincon fire is unknown. Likewise, frogs continued to persist in a few pools in Joaquin Canyon as of summer 2007.

The slow recovery of leopard frog populations in the drainage basins of the Rincon Mountains is in marked contrast to the recovery of fish populations in perennial stream channels documented by Lamberti and others (1991) in the Cascade Mountains, Oregon, and by Howell (2006) in the John Day River, Oregon. In the former study, cutthroat trout were extirpated from a channel reach by a debris flow, but populations recovered to pre-disturbance levels by the following year. In the John Day River study, post-wildfire floods, landslides, and debris flows eliminated steelhead and rainbow trout in moderate to high-intensity burn areas immediately after the fire, but fish began repopulating the reaches in the following year, and populations were near pre-disturbance levels four years after the fire. The short recovery period for aquatic habitats in the Oregon studies relative to that for tinajas in the Rincon Mountains, illustrates the difference in resilience between habitats in mesic environments and those in semiarid environments. In mesic environments, perennial stream flows are available to scour sediment deposits, transport pioneer organisms, and provide water for food sources and reproductive habitat immediately following the

disturbance, as opposed to semiarid environments where subsequent stream flow is intermittent and undependable.

The condition of leopard frog habitat in Chimenea Creek reflects the less catastrophic fire history of the watershed (Figure 4). Leopard frog surveys conducted in 1998–2005 show fluctuations in the number of frogs, but occupation of the channel by frogs was continuous throughout that period. The tinajas in Chimenea Creek currently support the densest leopard frog populations in the Rincon Mountains. The 24 tinajas in the channel exhibit a high degree of heterogeneity with varying amounts and texture of sediment and varying pool size and depth. Small patches of riparian and emergent vegetation are found at some pools. The patterns of leopard frog occupation of the 24 tinajas show that the lower reaches of Chimenea Creek provide the most consistently satisfactory habitat, with at least half of the tinajas between 1a and 1m occupied in most years by adult and juvenile frogs and tadpoles (Figure 5). Frog habitat is considerably more marginal upstream from tinaja 2a. The number of tinajas occupied by frogs in Chimenea Creek declined in fall 2000. Although this occurred at the same time as the number of frogs observed in Loma Verde Wash was declining, the reasons are not likely the same. Chimenea Creek was not significantly affected by the Box Canyon fire, which only burned parts of the watershed that drain into the channel downstream from the tinajas. In the marginal habitats of tinajas 2b through 2g and 2k, no frogs were observed after 2001 (with two exceptions).

Discussion

Sedimentation following large, crown fires is an extreme event that threatens the existence of lowland leopard frogs in Saguaro National Park and undoubtedly in other desert mountains

within the frogs' increasingly restricted range. The only prehistoric events that may have produced similar sedimentation would have been similar wildfires and perhaps extreme storm events, such as occurred in the neighboring Santa Catalina Mountains in July 2006. Either type of event would have been of low frequency with probable return intervals on a scale of centuries. Although those hypothetical events may have extirpated some leopard frog populations, the low frequency of events and the interconnectedness of leopard frog habitat in the Rincon Mountains to large streams and associated wetlands in the valleys below apparently permitted recovery of frog habitat.

The Rincon Mountains have been the site of five large wildfires from 1989 to 2003. Fires of this nature have become more frequent throughout the western United States because of fire-suppression practices instituted on public lands in the late 19th century that disrupted the fire-adapted ecosystems of western forests and resulted in increased forest density, underbrush growth, and accumulation of dead wood that fueled the destructive fires of recent decades. The high frequency of large wildfires, the slow recovery of habitat from excessive sediment deposition in the semiarid environment, and the fragmentation of habitat imperil the continued survival of the lowland leopard frog in Saguaro National Park.

Despite these developments, most leopard frog habitat that has been affected by post-wildfire sedimentation has recovered to some extent, and the frogs have reestablished in almost all of the canyons they occupied before the fires. Initial repopulation of Wildhorse Canyon, however, may not have occurred until 1996, nine years after the Chiva fire. As of summer 2007, sediment still filled the tinajas of Loma Verde Wash, nine years after the Box Canyon fire, and experimentally excavated tinajas had refilled, offering no prospect of recolonization by leopard frogs in the immediate future.

Chimenea Creek is the only drainage basin in the park in which aquatic ecosystems are functioning under a fire and hydrologic regime that approaches pre-European settlement conditions. As of summer 2007, the tinajas in Chimenea Creek provided the best habitat and contained the largest and healthiest lowland leopard frog population in Saguaro National Park. The absence of leopard frogs in marginal habitats after 2001 is more likely the result of drought than post-wildfire sedimentation, which could only have played a role after the 2003 Helens II fire. Because only 0.4 percent of the Chimenea Creek watershed was burned in that fire (Parker 2006), excessive sedimentation probably was not significant, and frogs are expected to recover.

The continued existence of the lowland leopard frog in the park depends on the magnitude and frequency of future wildfires, the amount of sediment deposited in channels and tinajas as a result of such fires, the recovery period following excessive sedimentation, and the ability of frogs to repopulate habitat once sediment has been flushed from the system. So far, only the Box Canyon fire has resulted in extirpation of leopard frogs from an entire watershed. In Wildhorse Canyon, leopard frog populations were greatly reduced but seem to be recovering. In Madrona Canyon and Rincon Creek, small leopard frog populations exist, but the extent to which they were affected by the Rincon fire and subsequent sedimentation is unknown. Sufficient evidence does not exist to predict the extent to which habitat will be disturbed following future wildfires, but it does appear certain that post-wildfire sedimentation presents an extreme stress to the leopard frog populations, and continued high frequency of severe wildfires, especially when accompanied by drought or other environmental stresses, could push some frog populations past the point of recovery.

The slow restoration of tinajas to functionality as leopard frog habitat as a result of large volumes of mobile sediment in storage upstream from the tinajas, infrequent scouring streamflows, or changes in channel hydraulics caused by excess deposition, decreases the probability that

leopard frog populations in affected channels will recover. Repopulation also is hindered by fragmentation of habitat that creates barriers, such as buried, desiccated tinajas, to colonization from healthy populations in other watersheds. Once a severe, crown fire has occurred, there are few management options available for protecting leopard frog habitat downstream from the burn area. Saguaro National Park fire managers have refrained from common post-wildfire treatments to reduce sedimentation, such as grass seeding, removal of dead or scorched trees or emplacement of structural controls (sediment traps, wood additions, weirs, check dams and gabions) in and near stream channels. Such practices have been criticized for effects on post-fire forest recovery and structure and long-term ineffectiveness (Beschta and others, 2004). Excavation of tinajas that have been buried in sediment has not proven effective. Consequently, excessive sedimentation following severe wildfires appears inevitable, although the total obliteration of habitat that occurred in Loma Verde Wash does not seem to have occurred in all fire-affected stream channels.

Natural recovery of tinajas to functioning aquatic habitat can take a decade or more, depending on the amount of sediment that is available for deposition from upstream storage sites and on the frequency and magnitude of streamflows in subsequent years. Lowland leopard frog populations apparently take longer yet to recover from the effects of habitat destruction and in the most extreme cases, recolonization is impossible because of destruction of refugia and isolation from other frog populations. Saguaro National Park managers have considered transplanting lowland leopard frogs into canyons that have physically recovered from post-wildfire sedimentation, but which have not been recolonized by frogs.

The presence of a healthy leopard frog population in Chimenea Creek suggests that preventive management holds the greatest promise of protecting this aquatic habitats in Saguaro National Park. The natural wildfire regime in the Rincon Mountains is one of extensive, high-

frequency, low-intensity burns. Modern conditions preclude restoration of a completely natural fire regime in the park, or in any other desert-mountain setting in which human land use is a significant factor. Nonetheless, the practice of prescribed burns and managed wildfires in the Chimenea Creek watershed likely has decreased the probability of severe wildfires and has not caused detectable harm to aquatic habitats in the stream channel. Leopard frog populations in the park are at continued risk from future wildfires, including those populations below areas that have burned earlier and in which some recovery has occurred. The recovery of ground cover in the Wildhorse Canyon and Rincon Creek watersheds and the presence of large areas that have not been burned in the past two decades puts leopard frog habitat at possible risk. In addition, the presence of exotic grasses in non-fire-adapted Sonoran-desert landscapes may present yet another modern hazard to aquatic habitat in lower elevation stream channels. Implementation of prescribed burns and removal of exotic grasses may alleviate the threat to leopard frog habitat in those channels.

Acknowledgements

Funding for this study was provided through the National Park Service–U.S. Geological Survey Water Quality Partnership Program.

Other acknowledgements TBA

References Cited

Comment [ts1]: I added commas in some citations for consistency. Ignore if not journal style, but all the reference are formatted the same.

- Arizona Fish and Game Department. 2006. Heritage Data Management System: Arizona Fish and Game Department Animal Abstract, AAABH01250. Available at http://www.azgfd.gov/w_c/edits/documents/Ranayava.fi.pdf (Accessed June 6, 2006)
- Baisan, C.H., and T.W. Swetnam. 1990. Fire history on a desert mountain range: Rincon Mountain Wilderness, Arizona, U.S.A. *Canadian Journal of Forest Research* 20: 1559-1569.
- Baker, V.R. 1977. Stream-channel response to floods, with examples from central Texas. *Geological Society of America Bulletin* 88: 1057–1071.
- Beschta, R.L., J.J. Rhodes, J.B. Kauffman, R.E. Gresswell, G.W. Minshall, J.R. Karr, D.A. Perry, F.R. Hauer, and C.A. Frissell. 2004. Postfire management on forested public lands of the western United States. *Conservation Biology* 18: 957–967.

- Bolin, S.B., and T.J. Ward. 1987. Recovery of a New Mexico drainage basin from a forest fire: Forest Hydrology and Watershed Management, Proceedings of the Vancouver Symposium. IAHS Publication 167: 191-198.
- Boulton, A.J., C.G. Peterson, N.B. Grimm, and S.G. Fisher. 1992. Stability of an aquatic macroinvertebrate community in a multiyear hydrologic disturbance regime. *Ecology* 73: 2192–2207.
- Bowers, J.E., and S.P. McLaughlin. 1987. Flora and vegetation of the Rincon Mountains, Pima County, Arizona. *Desert Plants* 8: 51-94.
- Bunn, S.E., and A.H. Arthington. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Science* 30: 492–507.
- Cannon, S.H., R.M. Kirkham, and M. Parise. 2001. Wildfire-related debris-flow initiation processes, Storm King Mountain, Colorado. *Geomorphology* 39: 171-188.
- Cannon, S.H., P.S. Powers, and W.Z. Savage. 1998. Fire-related hyperconcentrated and debris flows on Storm King Mountain, Glenwood Springs, Colorado, USA. *Environmental Geology* 35: 210-218.
- Cushing, C.E., and J.D. Allan. 2001. *Streams: Their ecology and life*. Academic Press, New York, 366 p.
- Esque, T.C., C.R. Schwalbe, L.A. DeFalco, R.B. Duncan, and T.J. Hughes. 2003. Effects of desert wildfires on desert tortoise (*Gopherus agassizii*) and other small vertebrates. *The Southwestern Naturalist* 48: 103–109.
- Esque, T.C. and C.R. Schwalbe. 2006. Nonnative grass invasions and fire in the Sonoran desert: USGS Fact Sheet. Available at <http://www.werc.usgs.gov/invasivespecies/i-esque2.pdf> (Accessed June 16, 2006)

- Fisher, S.G. 1986. Structures and dynamics of desert streams: In Whitford, W.G. (Ed.) Pattern and Process in Desert Ecosystems. University of New Mexico Press, Albuquerque: pp 119–139.
- Fisher, S.G., L.J. Gray, N.B. Grimm, and D.E. Busch. 1982. Temporal succession in a desert stream ecosystem following flash flooding. *Ecological Monographs* 53: 93–110.
- Gambradt, S.C., and L.B. Kats. 1997. Impact of chaparral wildfire-induced sedimentation on oviposition of stream-breeding California newts (*Taricha torosa*). *Oecologia* 110: 546–549.
- Giller, P.S., and B. Malmqvist. 1998. The biology of streams and rivers. Oxford University Press, Oxford, 296 p.
- Gore, J.A., J.R. Kelly, and J.D. Yount. 1990. Application of ecological theory to determining recovery potential of disturbed lotic ecosystems: research needs and priorities. *Environmental Management* 5: 755–762.
- Gray, L.J. 1981. Species composition and life histories of aquatic insects in a lowland Sonoran Desert stream. *American Midland Naturalist* 106: 229–242.
- Gray, L.J., and S.G. Fisher. 1981. Postflood recolonization pathways of macroinvertebrates in a lowland Sonoran Desert stream. *American Midland Naturalist* 106: 249–257.
- Grimm, N.B., and S.G. Fisher. 1989. Stability of periphyton and macroinvertebrates to disturbance by flash floods in a desert stream. *Journal of North American Benthological Society* 8: 293–307.
- Howell, P.J. 2006. Effects of wildfire and subsequent hydrologic events on fish distribution and abundance in tributaries of North Fork John Day River. *North American Journal of Fisheries Management* 26: 983–994.
- Howland, J.M., M.J. Sredl, and J.E. Wallace. 1997. Validation of visual encounter surveys: In Sredl, M.J. (Ed.), *Ranid Frog Conservation and Management*. Nongame and Endangered Wildlife

Program, Technical Report 121. Arizona Game and Fish Department, Phoenix, Arizona, pp. 21–36.

Lamberti, G.A., S.V. Gregory, L.R. Ashkenas, R.C. Wildman, and K.M.S. Moore. 1991. Stream ecosystem recovery following a catastrophic debris flow. *Canadian Journal of Fisheries and Aquatic Sciences* 48: 196–208.

MacLeod, A.H., M. Briggs, and E. Ostergaard. 2003. Identify and map water resources of the Rincon Mountain District of Saguaro National Park: Report to Water Resources Division of the National Park Service, Saguaro National Park, Desert Southwest Cooperative Ecosystems Park Studies Unit, Rincon Institute, Tucson, Arizona, 82 p.

Magirl, C.S., R.H. Webb, P.G. Griffiths, M. Schaffner, C. Shoemaker, E. Pytlak, S. Yatheendradas, S.W. Lyon, P.A. Troch, S.L.E. Desilets, D.C. Goodrich, C.L. Unkrich, A. Youberg, and P.A. Pearthree. 2007. Impact of recent Arizona storms. *Eos* 88: 5–7.

Martin, D.A., and J.A. Moody, J.A. 2001. The flux and particle size distribution of sediment collected in hillslope traps after a Colorado wildfire. *Proceedings of the Seventh Federal Interagency Sedimentation Conference*, Reno, Nevada, pp. III-40–III-46.

Meyer, J.L, W.H. McDowell, T.L. Bott, J.W. Elwood, I. Chanel, J.M. Melack, B.L. Peckarsky, B.J. Peterson, and P.A. Rublee. 1988. Elemental dynamics in streams. *Journal of North American Benthological Society* 7: 410–432.

Minshall, G.W. 2003. Responses of stream benthic macroinvertebrates to fire. *Forest Ecology and Management* 178: 155–161.

Moody, J.A. 2001. Sediment transport regimes after a wildfire in steep mountainous terrain: *Proceedings of the Seventh Federal Interagency Sedimentation Conference*, Reno, Nevada, pp. X-41–X48.

- Moody, J.A., and D.A. Martin. 2001. Post-fire, rainfall intensity-peak discharge relations for three mountainous watersheds in the western USA. *Hydrological Processes*. 15: 2981-2993.
- Paige, G.B., J.J. Stone, D.P. Guertin, R. McGee, and H. Blumenfeld. 2003. Runoff and erosion on a semi-arid grassland after a wildfire. *Proceedings Second International Wildfire Ecology and Fire Management Congress and Fifth Symposium on Fire and Forest Meteorology*, November 16-20, 2003; Orlando, Florida, American Meteorological Society. Available at http://ams.confex.com/ams/FIRE2003/techprogram/paper_65117.htm (Accessed June 16, 2006)
- Parker, J.T.C. 2006. Post-wildfire sedimentation in Saguaro National Park, Rincon Mountain District, and effects on lowland leopard frog habitat. U.S. Geological Survey Scientific Investigations Report 2006-5735: 35 p.
- Parsons, D.J., and S.J. Botti. 1996. Restoration of fire in national parks: In Hardy, C.C. and Arno, S.F. (Eds.) *The use of fire in forest restoration. Proceedings of Annual Meeting of the Society for Ecological Restoration*, Seattle, Washington, September 14-16, 1995. USDA Forest Service General Technical Report INT-GTR-341: 29-31. Available at http://www.fs.fed.us/rm/pubs/int_gtr341/gtr341_4.html. (Accessed August 9, 2006)
- Pilliod, D.S., R.B. Bury, E.J. Hyde, C.A. Pearl, and P.S. Corn. 2003. Fire and amphibians in North America. *Forest Ecology and Management* 178: 163-181.
- Pima County, Arizona. 2006. Pima County Multi-Species Conservation Plan: 346 p.. Available at <http://www.pima.gov/cmo/sdcp/> (Accessed February 17, 2006)
- Platz, J.E., and J.S. Frost. 1984. *Rana yavapaiensis*, a new species of leopard frog (*Rana pipiens* complex). *Copeia* 1984: 940-948.
- Reeves, G.H., L.E. Benda, K.M. Burnett, P.A. Bisson, and J.R. Sedell. 1995. A disturbance-based ecosystem approach to maintaining and restoring freshwater habitats of evolutionarily significant

units of anadromous salmonids in the Pacific Northwest. American Fisheries Symposium 17: 334–349.

Resh, V.H., A.V. Brown, A.P. Covich, M.E. Gurtz, H.W. Li, G.W. Minshall, S.R. Reice, A.L. Sheldon, J.B. Wallace, and R.C. Wissmar. 1988. The role of disturbance in stream ecology. Journal North American Benthological Society 7: 433–455.

Rinne, J.N. 1996. Short-term effects of wildfire on fishes and aquatic macroinvertebrates in the southwestern United States. North American Journal of Fisheries Management 16: 653–658.

Saguaro National Park. 2004. Draft Saguaro National Park Fire Management Plan Environmental Impact Statement: 206 p.

<http://www.nps.gov/applications/parks/sagu/ppdocuments/Draft%20Saguaro%20Fire%20Managment%20Plan.pdf> (Accessed August 7, 2006)

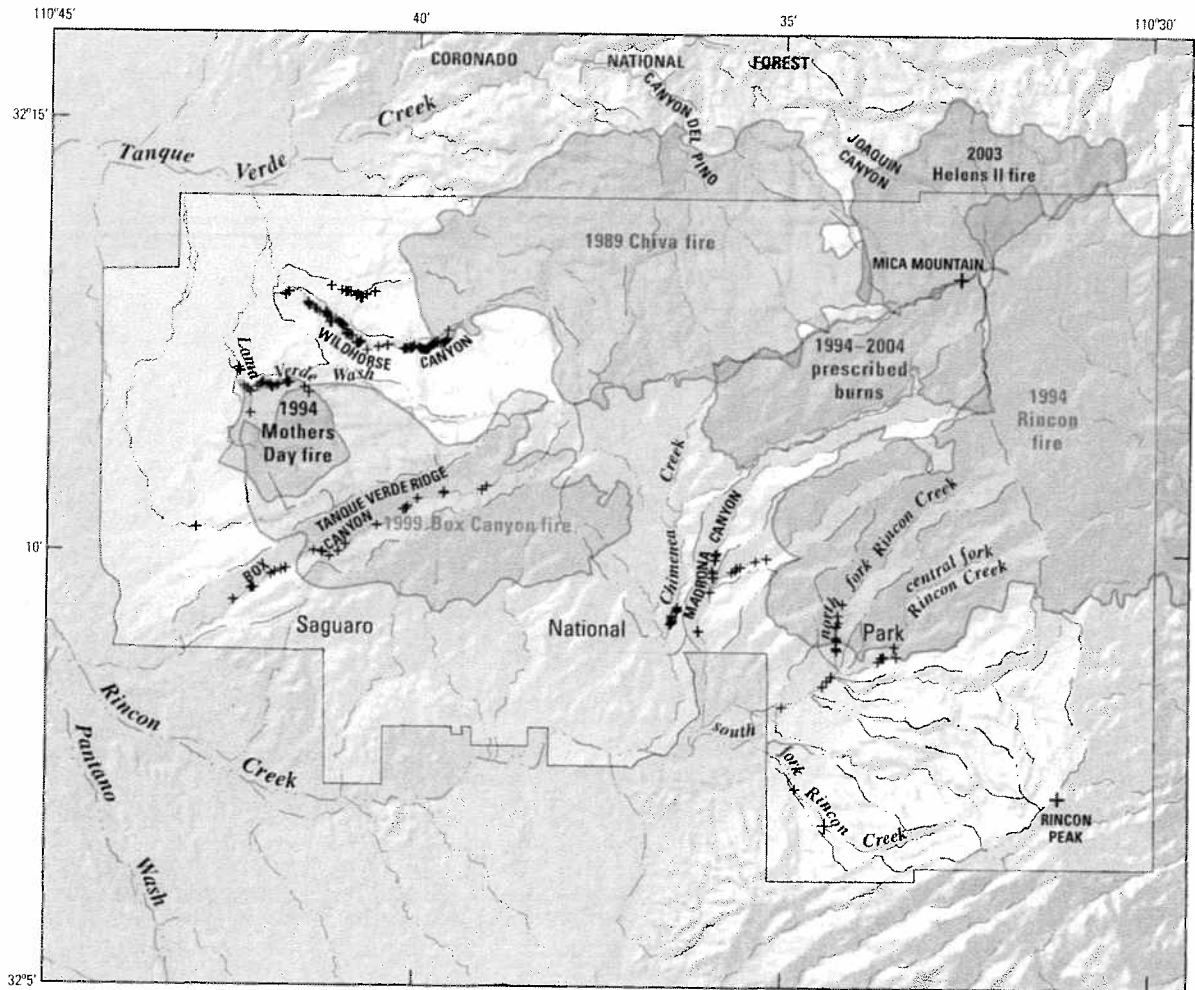
Selby, M.J. 1993. Hillslope materials and processes: Oxford University Press, Oxford, 451 p.

Sredl, M.J. 2005. *Rana yavapaiensis* Platz and Frost, 1984, Lowland leopard frog: In Lannoo, M.J. (Ed.) Amphibian declines: the conversation status of United States species. University of California Press, Berkeley, California: pp. 596–599.

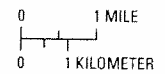
Sredl, M.J., E.P. Collins, and J.M. Howland. 1997. Mark-recapture studies of Arizona leopard frogs: In Sredl, M.J. (Ed.), Ranid Frog Conservation and Management. Nongame and Endangered Wildlife Program, Technical Report, Number 121: 1–35. Arizona Game and Fish Department, Phoenix, Arizona.

Sredl, M.J., and L.S. Saylor. 1998. Conservation and Management Zones and the role of earthen cattle tanks in conserving Arizona leopard frogs on large landscapes: In Feller, J.M. and D.S. Strouse (Eds.), Environmental, Economic, and Legal Issues Related to Rangeland Water

- Developments. Center for the Study of Law, Science and Technology, Arizona State University, Tempe, Arizona: pp. 211–225.
- Veenhuis, J. 2002 Effects of wildfire on the hydrology of Capulin and Rito De Los Frijoles Canyons, Bandelier National Monument, New Mexico. U.S. Geological Survey Water-Resources Investigations Report 02–4152, 39 p.
- Wells, W.G. 1987. The effects of fire on the generation of debris flows in southern California: In Costa, J.E. and Wieczorek, G.F. (Eds.) Debris flow/avalanches, Reviews Engineering Geology, Geological Society of America 7: 105–114.
- Whipple, K.X., G.S. Hancock, and R.S. Anderson. 2000. River incision into bedrock: Mechanics and relative efficacy of plucking, abrasion, and cavitation. Geological Society of America Bulletin 112: 490–503.
- Wohl, E.E. 1998. Bedrock morphology in relation to erosional processes: In Tinkler, K.J., Wohl, E.E. (Eds.) Rivers over rock—fluvial processes in bedrock channels. Geophysical Monograph 107. American Geophysical Union, Washington, D.C. pp. 133–151.



Base from U.S. Geological Survey
digital data, 1:100,000, 1982
Universal Transverse Mercator
projection, Zone 12



- EXPLANATION**
- BURN AREA
 - BOUNDARY OF NATIONAL PARK
 - BOUNDARY OF BASIN
 - LEOPARD FROG LOCATION



Figure.1 Location map of study area and extent of large fires occurring 1989–2003.

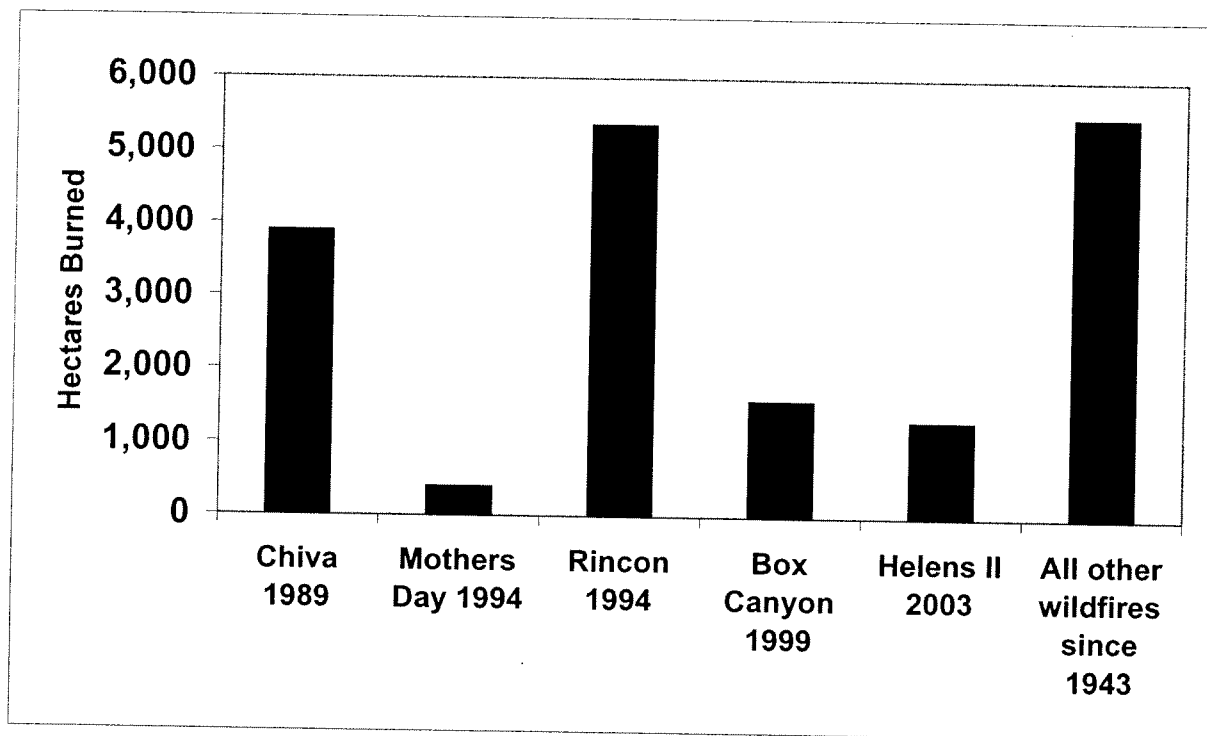


Figure 2. Graph showing fire history in Rincon Mountains since 1943.

11

11

A. Before fire



B. After fire



Figure 3. Comparative photographs showing post-wildfire sedimentation in tinajas in Loma Verde Wash from the Box Canyon fire of 1999. A. Spring, 1996. Open tinaja with water visible in middle of photograph. B. Spring, 2001. Tinaja buried in sand. Photographs by Don E. Swann, Saguaro National Park.