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INTRODUCTION

The Spring 2006 meeting of the Hydrology Section of the Arizona-Nevada Academy of Science took place at the University of Arizona in Tucson on April 8. The Hydrology Section organizers wish to extend their thanks to Ms. Louella Holter with the Bilby Research Center, Northern Arizona University, for her editorial assistance on this publication. Dr. Peter Ffolliott, University of Arizona, was the chairperson for the 2006 Hydrology Section meeting. This volume is published by the University of Arizona, Tucson.

George Zaimes
Tucson, Arizona

A BRIEF HISTORY OF THE HYDROLOGY SECTION

Peter F. Ffolliott,[1] Daniel G. Neary,[2] and Gerald J. Gottfried[3]

It is appropriate at this 50th annual meeting of the Arizona-Nevada Academy of Science to present a brief history of the Hydrology Section, which is holding its 36th annual session at this milestone event. The Arizona-Nevada Academy of Science is one of only a few of the other 262 societies and academies of science affiliated with the American Association for the Advancement of Science to include a "Hydrology Section" within its organization. Inclusion of a Hydrology Section into the Arizona-Nevada Academy of Science is deemed appropriate and relevant because of the importance placed on the limited water resources by the people in this region. A brief history of the Hydrology Section from its inception to the present is the focus of this paper.

THE BEGINNING

The inaugural meeting of the Hydrology Section was held in the Student Union at Arizona State University on April 22, 1971. This meeting, organized largely through the efforts of Dan Evans, then head of the Department of Hydrology at the University of Arizona, was mainly a "trial balloon" to assess the level of interest in forming a Hydrology Section within the existing Arizona Academy of Science.[4] Twenty-nine papers on varying topics related to hydrology and water resources were presented at the meeting, which attracted about 35 hydrologists, watershed managers, and other interested participants. That the hoped-for level of interest was attained at this meeting is witnessed by the fact that the Hydrology Section has met annually since 1971, with the exception of 1992 when the annual meeting of the Arizona-Nevada Academy of Science was incorporated into the larger meeting of the Southwestern and Rocky Mountain Division of the American Association for the Advancement of Science held in Tucson.

A co-convener of the Hydrology Section's sessions until 1995 was the Arizona Section of the American Water Resources Association. This organization helped to publicize the annual meetings of the Arizona-Nevada Academy of Science (and therefore the Hydrology Section session), announce the call for papers for presentation in the Hydrology Section's sessions, and sponsor publication of the annual proceedings (see below). The Arizona Section of the American Water Resources Association also sponsored a series of water-related conferences that were generally held in the fall to complement the spring meetings of the Hydrology Section.

VENUES

Venues for the Hydrology Section's sessions have been, and continue to be, the institutions of higher education hosting the annual meetings of the Arizona-Nevada Academy of Sciences. These universities and colleges include Arizona State University in Tempe, Prescott College, the University of Arizona in Tucson, Northern Arizona University in Flagstaff, the University of Nevada at Las Vegas, Glendale Community College, and Midwestern University in Glendale, Arizona.

SESSION FORMATS

Formats for the Hydrology Section's sessions have been variable, mostly in the initial years of the Hydrology Section's existence. In some instances keynote speakers have been invited to present a review of a specific topic of current interest, and in a few instances a general theme has been adopted for the annual session, with most of the papers focusing on that theme. However, at most of the Hydrology Section's sessions, volunteer papers on a variety of local and regional water-related topics have been presented to offer a large diversity of topics for presentation. This format has proven to be the most successful,

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largely because of the wide diversity of interests represented by the sessions' participants. It has also been an opportunity for students at all levels to gain valuable experience in presenting and publishing research.

Calls for papers for presentation in the Hydrology Section's sessions have been, and continue to be, solicited primarily through the (October) newsletter of the Arizona-Academy of Science. Interested presenters submit abstracts of their proposed presentations to the chairperson of the Hydrology Section for review, possible acceptance, and, if accepted for presentation, inclusion in the agenda for the session. These chairs, who serve on an annual basis, are either elected by the membership of the Hydrology Section, appointed, or otherwise "volunteered" for the annual sessions. Recent chairs of the Hydrology Section have been Martin Karpiscak, University of Arizona; Don Young, Attorney General's Office, State of Arizona; Fred Amalfi, Aquatic Consulting and Testing, Inc., Phoenix; Dave Kreamer, University of Nevada at Las Vegas; Chuck Avery, Northern Arizona University; Malchus Baker, Roy Jemison, and John Rinne, all of the Rocky Mountain Research Station, USDA Forest Service; and the three authors of this paper.

Abstracts of the papers selected for presentation are published in a special issue of the Journal of the Arizona-Nevada Academy of Science or, in recent years, a "proceedings" of the annual meeting. These publications include the agenda for all of the sessions in the annual meeting, minutes of the annual meeting of the previous year, the business report and reports of the Academy committees, and other information relative to the annual meeting and other Academy activities.

Until 1982, the meetings took place all day Friday plus Saturday morning; they were shortened to a single day (Saturday) to accommodate the commitments and academic schedules of many attendees. Even with the two-day schedule, however, the Hydrology Section commonly scheduled concurrent sessions to provide a forum for all of the papers to be presented. In excess of 45, and in one year as few as 5 papers have been presented in the annual sessions of the Hydrology Section.

TOPICS OF PAPERS

At least 669 papers have been presented in the Hydrology Section's sessions since the inaugural meeting. Topics of these papers include the results of baseline studies of components of the hydrologic cycle; effects of land management activities on soil-water relationships, surface erosion, and sedimentation regimes; physical and economic feasibility of practices, projects, and programs to sustain limited water supplies; and planning processes and policy assessments in relation to water resources management. A summary of the papers presented in the first 25 years of the Hydrology Section's existence was presented by Ffolliott et al. (1997) at the Annual Meeting of the Arizona-Nevada Academy of Science at the University of Nevada at Las Vegas. These papers were grouped into the following topical categories in an effort to recognize whether a change in emphasis had occurred over the course of the Hydrology Section's initial 25-year period:

- Hydrologic Cycle – precipitation, interception, infiltration, evapotranspiration and soil water, and runoff (overland flow) and streamflow
- Erosion and Sedimentation – erosion processes and resultant sediment yields
- Surface Water Quality – physical, chemical, and biological constituents of surface water
- Ground Water Resources – rates of aquifer replenishment and physical, chemical, and biological constituents
- Geology and Geomorphology – geologic formations, geologic-hydrologic relationships, and geomorphic features
- Snow Hydrology – snowpack accumulation and melt patterns, physical and chemical properties, and snowpack-runoff efficiencies
- Riparian Ecosystems & Aquatic Environments – hydrologic relationships, ecological significance, and fish habitats
- Fire and Fire Effects – impacts of fire on hydrologic processes and water resources
- Water Harvesting Practices – increasing the availability of water supplies, alternative designs of systems, and economic considerations
- Irrigation Practices – alternative irrigation regimes, crop response to irrigation, and feasibility studies
- Urban Hydrology – impacts of developments on the hydrologic cycle and water regimes
- Economics – appraisals and evaluations of water resources' initiatives, marketing considerations, and projections of future supplies and demands

- Planning and Policy Issues – planning processes, policy assessments, policy formulations for water resources management
- Other Topics

General conclusions include the following:

- Papers on the components of the hydrologic cycle represented the majority of the presentations in the Hydrology Section's sessions throughout this first 25-year period.
- Papers on erosion and sedimentation processes, water quality, geology and geomorphology, ground water resources, snow hydrology, water harvesting, planning and policy topics, and economics remained more-or-less unchanged in the 25-year period.
- Papers on riparian ecosystems and aquatic environments and fire and fire effects increased substantially in the 1990s, mostly in response to the increasing interest of the public in these topics.
- The comparatively limited papers presented on the other topics largely precluded any inferences regarding a possible change in emphasis.

This summary has been updated here to include all of the papers presented in all of the Hydrology Section's sessions since its inception in 1971. These papers have been grouped into the same topical categories considered by Ffolliott et al. (1997) to indicate their depth and breadth and especially to expand on the findings of the earlier study. The papers have also been grouped into decades—the 1970s, 1980s, 1990s, and midway through the 2000s—and summarized by the percent of the papers presented in the respective topical categories in these decades. The results of these summaries are presented in Table 1. Although these summaries cannot be analyzed statistically, general inferences can be drawn relative to whether the papers presented reflect a changing emphasis in hydrology and water resources in the Southwest in the past 35 years. It should be mentioned that these inferences can be somewhat misleading because potential presenters might opt to present papers on their technical specialties at other symposia, conferences, and professional meetings that focus on their respective specialties.

- Papers on the components of the hydrologic cycle consistently represent the majority of the presentations made throughout the history of the Hydrology Section's sessions.
- Papers on riparian systems and aquatic environments and fire and fire effects have increased since 1971 in (the apparent) response to the increasing importance people have placed on these topics in recent years.
- Papers on erosion and sedimentation, snow hydrology, water harvesting practices, and economics have remained largely unchanged since 1971.

Table 1. Summary of papers presented at Hydrology Section meetings by topic and decade.

	Percent of Papers			
Topic	1970	1980	1990	2000
Hydrology cycle	34	28	28	35
Erosion and sedimentation	5	4	8	6
Water quality	15	14	9	5
Ground water resources	10	15	5	2
Geology and geomorphology	3	2	2	6
Snow hydrology	4	6	7	2
Riparian systems and aquatic environments	0	1	16	11
Fire and fire effects	1	1	10	16
Water harvesting	2	4	3	0
Irrigation practices	2	0	0	0
Urban hydrology	1	1	0	0
Economics	4	9	2	4
Planning and policy issues	17	11	8	3
Other	2	4	2	10

- Papers on water quality, ground water resources, and planning and policy issues have declined in the number of presentations.

- Papers on "technology transfer mechanisms" such as the World Wide Web have been the main contributor to the increased number of papers in the "other" category.

- Inferences on the papers presented on the other topics are difficult to make because of the comparatively small numbers involved.

PUBLICATION OF THE PAPERS

Most of the papers presented in the Hydrology Section's sessions have been, and continue to be, published in the annual proceedings, "Hydrology and Water Resources in Arizona and the Southwest." The Hydrology Section is the only section in the Arizona-Nevada Academy of Science that publishes its own proceedings. These proceedings are distributed to the participants in the sessions, other water resources and watershed managers in the region and elsewhere, and science libraries and other depositories of water-related information. An exception to the publication of these annual proceedings occurred in the three years of 1992, 1993, and 1994, when attendance at the annual sessions declined to only a few participants, and as a consequence not enough papers were presented to warrant a formal publication of the proceedings. The publication of their papers in the annual proceedings of the Hydrology Section's sessions does not preclude the presenters' publishing their contributions in other formal outlets, and in fact it is encouraged.

A FINAL COMMENT

While we recognize that the Hydrology Section of the Arizona-Nevada Academy of Science is a unique element of the scientific societies and academies of science that are affiliated with the American Association for the Advancement of Science, interest and participation in the Hydrology Section has waned in recent years. One likely reason for this decline has been the increasing number of symposia, conferences, and other meetings on a wide range of water-related issues that are continuously held in Arizona and throughout the region. Such an activity is the Annual Meeting of the Arizona Hydrological Society, where water-related topics of statewide interest and concern are reviewed by invited speakers. It is hoped, however, that one outcome of this 50th Annual Meeting of the Arizona-Nevada Academy of Science will be a renewed interest in the Hydrology Section and the other sections in the years ahead.

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OCCURRENCE AND PERSISTENCE OF WATER-REPELLENT SOILS ON THE STERMER RIDGE WATERSHEDS FOLLOWING THE RODEO-CHEDISKI WILDFIRE

Cody L. Stropki,[1] Peter F. Ffolliott,[1] Leonard F. DeBano,[1] and Daniel G. Neary[2]

Wildfires have been shown to cause water repellency in the underlying soils by restricting infiltration of water into the soil profile and thereby producing overland flow (DeBano and Krammes 1966). Overland flow caused by the water-repellent layer can cause excessive soil erosion, resulting in sediment-laden streams. The water-repellent layer is produced when organic hydrophobic substances are volatilized during the combustion of surface litter layers. These volatilized compounds are then distilled downward into the soil where they condense on cooler soil particles and form a hard-to-wet layer (DeBano et al. 1970; Savage 1974; DeBano 1981, 1999, 2003; Doerr et al. 2000). This mechanism contributed to the extensive water repellency found in the soils on the Stermer Ridge watersheds following the Rodeo-Chediski wildfire of 2002.

The Rodeo-Chediski wildfire of 2002, the largest and most costly in Arizona's history, damaged, destroyed, or disrupted the hydrologic functioning on many of the 475,000 acres of burned ponderosa pine forest. The degree to which the hydrologic functioning will return to pre-fire functioning, if ever, is open for conjuncture. It is vital, therefore, that the impacts of this historical event be documented in terms of time-trend response of the persistence of water-repellent soils in a ponderosa pine forest.

METHODOLOGY

Study Area

Two nearly homogenous watersheds, 60 acres each, were established in 1972 by the University of Arizona and the USDA Forest Service along Stermer Ridge, located about 9 miles southwest of Overgaard, Arizona. These watersheds are located in uneven-aged ponderosa pine forests at the headwaters of the Little Colorado River. Much of the information on the hydrologic and ecologic functioning of ponderosa pine forest in the region was obtained on volcanic soils before these watersheds were established. The main objective of the Stermer Ridge watersheds, therefore, was to obtain baseline data on the hydrologic functioning and ecologic changes of ponderosa pine forests growing on sedimentary soils (Ffolliott and Baker 1977).

These watersheds both have the relatively flat topography that is common on the Colorado Plateau at elevations between 6800 and 7000 feet. Cretaceous undivided material similar to the Coconino Sandstone formation lies beneath the watersheds. McVickers soils in the Soldier-Hogg-McVickers association are the major soils found on both watersheds. Hendricks (1985) described these soils as being moderately well drained with a fine, sandy loam texture. Sixty-five percent of the annual precipitation of 20–25 inches falls from late October to April, coming as snow, rain, or a combination thereof, and the remainder falls during the summer monsoonal rainstorms occurring from July to early September. More than 90 per-cent of the pre-fire intermittent streamflow was a result of snowmelt runoff or winter rains. Summer monsoon storms, while often intense, rarely produced significant stormflows before the wildfire.

The watersheds were "decommissioned" in 1977 after the completion of the baseline studies (Ffolliott and Baker 1977). However, the control structures (3 ft H-flumes) were left in place in anticipation of future streamflow monitoring efforts. After the Rodeo-Chediski wildfire, these control structures were refurbished and re-instrumented with water level recorders and a weather station was reestablished on the site. The original 30 sample plots installed on each watershed to sample on-site hydrologic and ecological parameters were reestablished to study the impacts of the Rodeo-Chediski wildfire on hydrologic processes and ecological changes (Ffolliott and Neary 2003a, 2003b; Neary et al. 2003). A classification system relating fire severity at a sam-

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ple plot to fire-induced soil changes (Hungerford 1996) was extrapolated to a watershed basis to determine the relative proportions of the watersheds that burned at low, moderate, and high fire severity (Wells et al. 1979). This assessment indicated that one of the Stermer Ridge watersheds experienced a high-severity, stand-replacing fire, while the other had been exposed to a low- to moderate-severity, stand-modifying fire.

FIELD SAMPLING

Water repellency of the soils on the watersheds after the Rodeo-Chediski wildfire was determined following the summer monsoonal seasons of 2002, 2003, 2004, and 2005 and the snowmelt runoff seasons of 2003, 2004, and 2005 to relate water repellency to fire severity and to estimate change in water repellency over time following fire. Soil water repellency was measured by the Water Drop Penetration Time (WPT) method outlined by Letey et al. (2000). The sampling procedure began by removing the litter and duff layers on each sample plot to expose the bare mineral soil. Then a drop of distilled water was placed on the mineral soil surface with an eye dropper and the time it took for the drop to penetrate into the surface was recorded. This procedure was then repeated and the longest of the two times was used to assign four levels of water repellency according to the following criteria, developed by the National Wildfire Coordinating Group (2003): Strong = more than 40 sec, moderate = 10–40 sec, slight = less than 10 sec, and none = 0 sec.

The occurrence and degree of water repellency in relation to fire severity at a sample plot was extrapolated to a watershed basis using knowledge of the incidence of water repellency on the watersheds. The relationships between water repellency and the physiographic features of the watersheds were assessed by grouping the plots according to hillslope position (lower, middle, upper), slope percent (> 6 percent, 6–10 percent), and aspect (quadrant). The levels of water repellency were grouped by their frequencies of occurrence, and chi-square tests were used to determine significant differences in the level of water repellency among the various physiographic parameters (Zar 1999). All tests were conducted at an alpha level of 0.10.

RESULTS AND DISCUSSION

Watershed Differences

Nearly two-thirds of the soils on the Stermer Ridge watershed burned by a high-severity fire had a strong level of water repellency when first measured following the summer monsoonal season of 2002. The remaining third of the soils had a moderate level of water repellency. Strong water-repellency levels were measured in only one-third of the soils on the watershed that burned at low to moderate fire severity and 15 percent had moderate water repellency. Almost half of the soils on the less severely burned watershed had slight or no water repellency (Figure 1). These results were similar to the findings of Campbell et al. (1977), who found a high occurrence of strong water repellency on sites where soils were exposed to high fire severity, following a wildfire in a ponderosa pine forest on limestone soils near Flagstaff, Arizona. The Stermer Ridge results were also consistent with the conceptual model of the effects of fire severities on soil resources proposed by DeBano et al. (1995), which indicates that a fire of high severity causes more hydrophobic substances to condense in the soil profile compared to a less severe fire.

Due largely to the extensive water-repellent soils on both watersheds following the Rodeo-Chediski wildfire, historically high peak streamflows occurred during the summer monsoonal seasons of 2002 (Ffolliott and Neary 2003a, 2003b; Neary et al. 2003). The highest post-fire peak streamflow event occurred on the severely burned watershed, with an estimated peak streamflow of 232 ft^3/sec, or 2350 times greater than that measured during the 1972–1976 pre-fire period. This flow also represents the highest known post-fire peak flow recorded in the montane forests of the southwestern United States. The highest peak streamflow on the low to moderately burned watershed was about half the magnitude of the severely burned watershed, but it was also far in excess of pre-fire measurements.

The proportion of the severely burned watershed having a strong level of water repellency gradually declined during the first three sampling periods compared to the water repellency on the low to moderately burned watershed (Figure 1). Parenthetically, the appearance of a small increase in the proportion of the former watershed having soils with a condition of strong water repellency was likely caused by the inability to measure water repellency at the same location on a sample plot on a continuing basis because of the destructive nature of the sampling procedure.

Nearly all water repellency had broken down on both watersheds 3 years after the fire, when about 75 percent of the severely burned watershed and more than 95 percent of the low to moderately

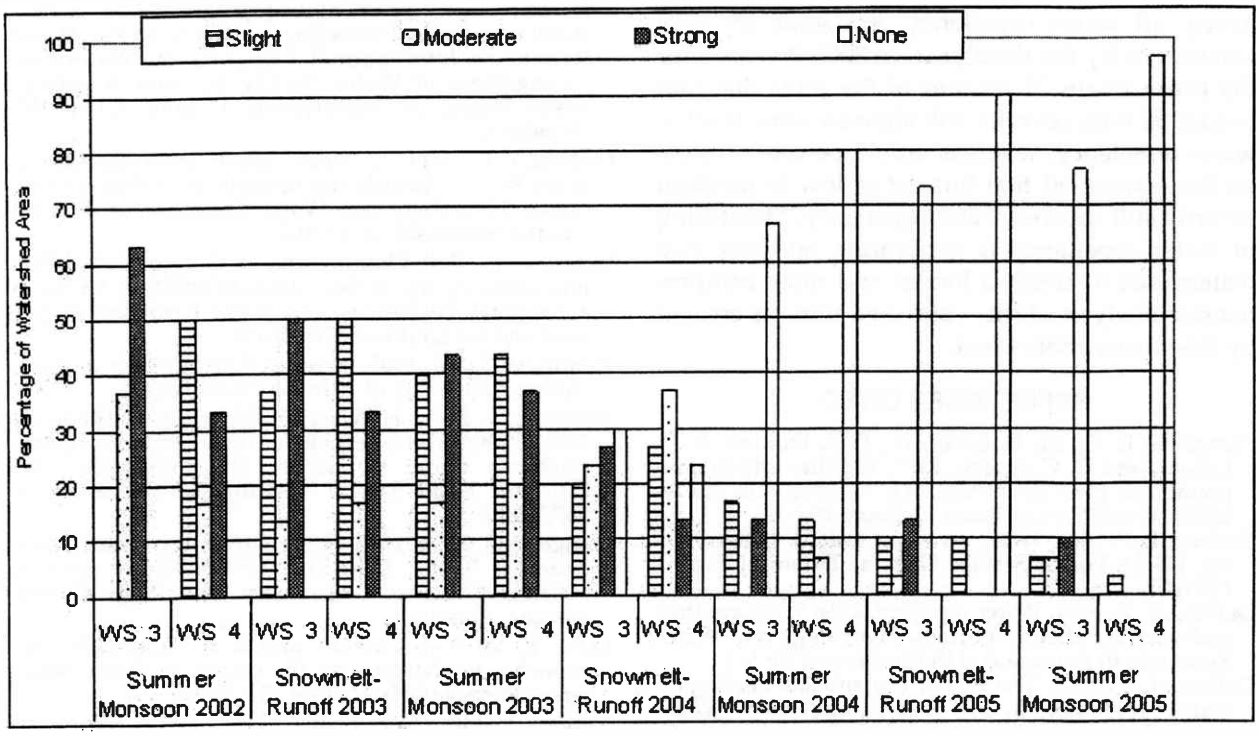

Figure 1. Changes in the occurrence of water-repellent soils on the Stermer Ridge watersheds following the Rodeo-Chediski wildfire of 2002.

burned watershed displayed no water repellency (Figure 1). This finding could be attributed to the continued erosion of the water-repellent soils, to the point were the water-repellent layer was eroded away (Garcia et al. 2004). Also, continued exposure to wetting and drying generally decreases the severity of water repellency in soils over time (Neary et al. 2005).

Not many long-term monitoring studies have been conducted on the longevity of soil water repellency following fire. However, when it has been measured, the results vary widely and appear to be dependent on site-specific characteristics (Doerr et al. 2000). The study reported in this paper shows that a small proportion of water repellency can remain 3 years after fire, which is similar to other findings. Campbell et al. (1977), for example, reported water-repellent soils persisting for 4 years, and Huffman et al. (2001) found water-repellent soils persisting 22 months after wildfire in a ponderosa pine forest on the Colorado Front Range. Water repellency in soils in lodgepole pine stands in the Upper Cascades of Oregon still persisted 6 years after wildfire (Dyrness 1976).

Physiographic Parameters

After the first summer monsoonal rains, the middle to lower slopes of the Stermer Ridge watersheds exhibited a higher proportion of strong water repellency than was found on the upper slopes. This difference was attributed largely to the generally deeper soils and greater deposition of organic matter on the middle to lower slopes. Little relationship was evident between water repellency of the soils and slope percent or aspect, probably because both watersheds are relatively flat and mostly north facing.

SUMMARY

Many studies have documented the hydrologic importance of post-fire water repellency in soils on infiltration, overland flow, and soil erosion (Savage et al. 1972; DeBano and Rice 1973; Campbell et al. 1977; DeBano 1981, 1999, 2003; Huffman et al. 2001, and others). This study evaluated the spatial and temporal persistence of water repellency in soils on the Stermer Ridge watersheds following the Rodeo-Chediski wildfire. Water repellency in

soils began disappearing 2 years after the fire and nearly all water repellency was gone on both watersheds by the third year. In 2005, 3 years after the fires, nearly 25 percent of the plots that had burned at high severity still showed some level of water repellency, whereas only 3 percent of plots on the watershed that burned at low to medium severity still showed water repellency. Monitoring of water repellency is continuing on these two watersheds to create a longer and more comprehensive analysis of the watershed impacts created by this catastrophic event.

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EVAPORATION OF SOIL MOISTURE ON BURNED WATERSHEDS: AN ARIZONA CASE STUDY

Cody L. Stropki,[1] Peter F. Ffolliott,[1] Leonard F. DeBano,[1] and Daniel G. Neary[2]

The effects of a fire on soil moisture are linked to the loss of vegetation during the combustion process which (in turn) lowers evapotranspiration losses, leaving more water in the soil than would be present in the absence of burning. Overland flow and ultimately streamflow are generally more responsive to post-fire precipitation events as a consequence of this increased soil moisture (DeBano et al. 1998; Neary et al. 2005). However, this situation does not hold true for all cases. Campbell et al. (1977) observed a reduction in soil moisture in the upper 12 inches of the limestone soil profile on a 20-acre watershed near Flagstaff, Arizona, after two-thirds of the pre-fire ponderosa pine forest overstory and much of the herbaceous understory were destroyed by a wildfire in comparison to an unburned (control) watershed. Greater overland flow on the burned watershed was the assumed factor underlying this difference. To determine whether this situation is the exception, evaporation of soil moisture on two watersheds in the ponderosa pine forests burned by the Rodeo-Chediski wildfire are compared to each other and to field capacity through three-plus years of post-fire sampling.

STUDY PROTOCOL

Two nearly homogeneous watersheds, 60 acres each, were established in 1972 by the University of Arizona and the USDA Forest Service along Stermer Ridge about 8 miles southwest of Overgaard, Arizona, to obtain baseline hydrologic and ecological information on sandstone soils (Ffolliott and Baker 1977). These watersheds possess the flat topography (most of the slopes are less than 10 percent) that is common on the Colorado Plateau. Elevations range from 6800 to 7000 feet. Beneath each watershed lies Cretaceous undivided material with mineralogy that is similar to that of the Coconino Sandstone formation. McVickers soils in the Soldier-Hogg-McVickers association characterize the watersheds. Hendricks (1985) described these moderately well to well drained soils as possessing a fine, sandy loam texture. Sixty-five percent of the annual precipitation of 20–25 inches falls from October to April, much of it as snow. The remaining precipitation falls mostly in the summer monsoonal season from July to early September. Most of the intermittent streamflow from the Stermer Ridge watersheds results from snowmelt-runoff or winter rains. The summer monsoonal storms rarely produced significant stormflows before the wildfire.

The watersheds were "mothballed" in 1977 upon completion of baseline studies. However, the control sections (3 ft H-flumes) were left in place in anticipation of future streamflow monitoring efforts. Such a need arose after the Rodeo-Chediski wildfire (Ffolliott and Neary 2003a, 2003b; Neary et al. 2003, 2005, 2006). The control sections were refurbished and re-instrumented with water-level recorders, a weather station on the site was re-established, and the permanently located sample plots established on each watershed were relocated to monitor the impacts of the Rodeo-Chediski wildfire on hydrologic and ecological processes. A classification system relating fire severity to soil response to burning (Hungerford 1996) was extrapolated to a watershed basis to determine the relative portions of the Stermer Ridge watersheds burned at low, moderate, and high fire severities (Wells et al. 1979). The extrapolation indicated that one of the Stermer Ridge watersheds experienced a high-severity, stand-replacing fire, whereas the other watershed was exposed to a low to medium-severity, stand-modifying fire.

Composited soil samples 4 inches in depth were obtained on a subsample of 15 of the 30 sample plots located on each of the watersheds. Three-plus years of post-fire samples were taken in the study; the most intensive sampling occurred in the late

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summer and autumn of 2002, after cessation of the wildlife, and throughout the growing season of 2003. Soil water in these subsamples was determined gravimetrically. The resultant drying patterns of these samples were assumed to be indicative of the magnitudes and spatial characteristics of the post-fire soil evaporation. Field capacity of the soil on unburned sites near the watersheds was determined to represent a reference in the comparisons.

RESULTS AND DISCUSSION

The results from this study differed somewhat from those obtained by Campbell et al. (1977), who reported that the loss of soil moisture on the severely burned watershed was greater than the loss of soil moisture from the unburned watershed in the 3 post-fire years of sampling in their study. While soil on the severely burned watershed dried (comparatively) quickly after the wildfire, the total demand for soil moisture by plants was less on the burned watershed than on the unburned watershed because of reduced evapotranspiration. These differences decreased, however, as a protective herbaceous cover became reestablished on the burned watershed. Conversely, soil moisture in the surface soil layers on the Stermer Ridge watershed that burned at a high severity was not different on most sampling dates than that on the watershed burned at low to moderate severity (Figure 1). One exception occurred on a sampling date in November 2002, when soil moisture on the watershed that burned at a high severity was significantly higher than that on the watershed burned at a low to moderate severity.

Seasonal differences in soil moisture were observed in 2003. Soil moisture was higher on both watersheds following the periods of snowmelt-runoff and prolonged winter rains and the summer monsoonal storms. Soil moisture was lower in the intervening dry periods. Trends for the other (less intensive) sampling periods in the study were less clear.

Soil moisture reached field capacity on two sampling dates in the autumn of 2002, within 5 months of the wildfire. That field capacity was not reached in the remainder of the study period was not surprising, however, as the three-plus years of post-fire sampling coincided with a prolonged drought period in the area.

CONCLUSIONS

Post-fire soil moisture regimes on watersheds in ponderosa pine forests on limestone (Campbell et al. 1977) and sandstone soils on the Stermer Ridge watersheds were different. Furthermore, fire severity apparently played a minor role in the post-fire soil moisture regime of the sandstone soils on Stermer Ridge. However, inferences drawn from the findings reported in this paper should be considered within the context of the infrequent post-fire sampling of soil moisture and below-average precipitation regime that persisted throughout the study period. Further monitoring of soil moisture following fire in ponderosa pine forests is suggested.

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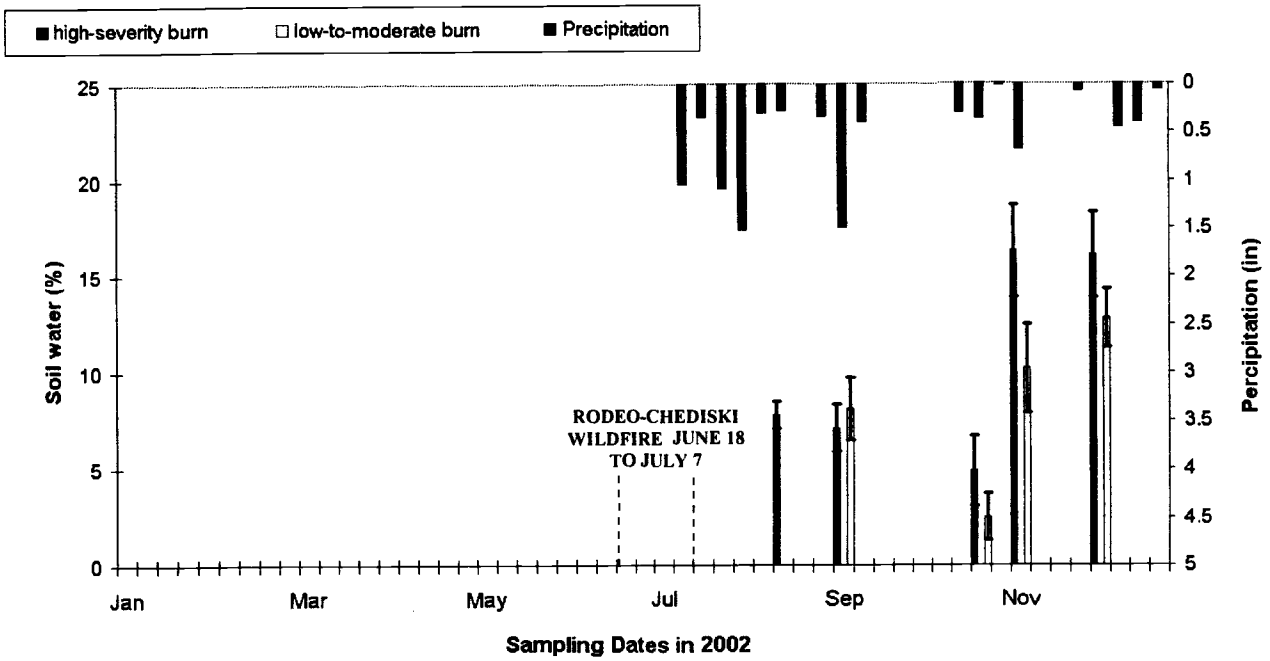


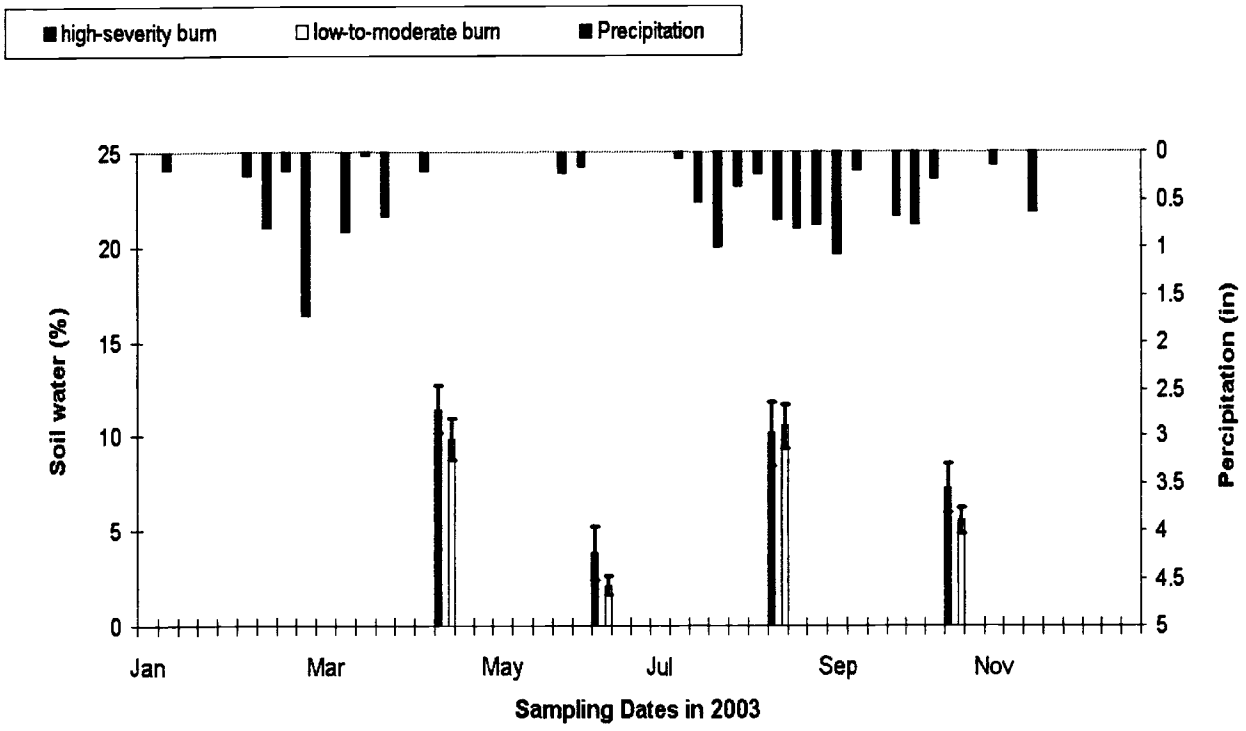
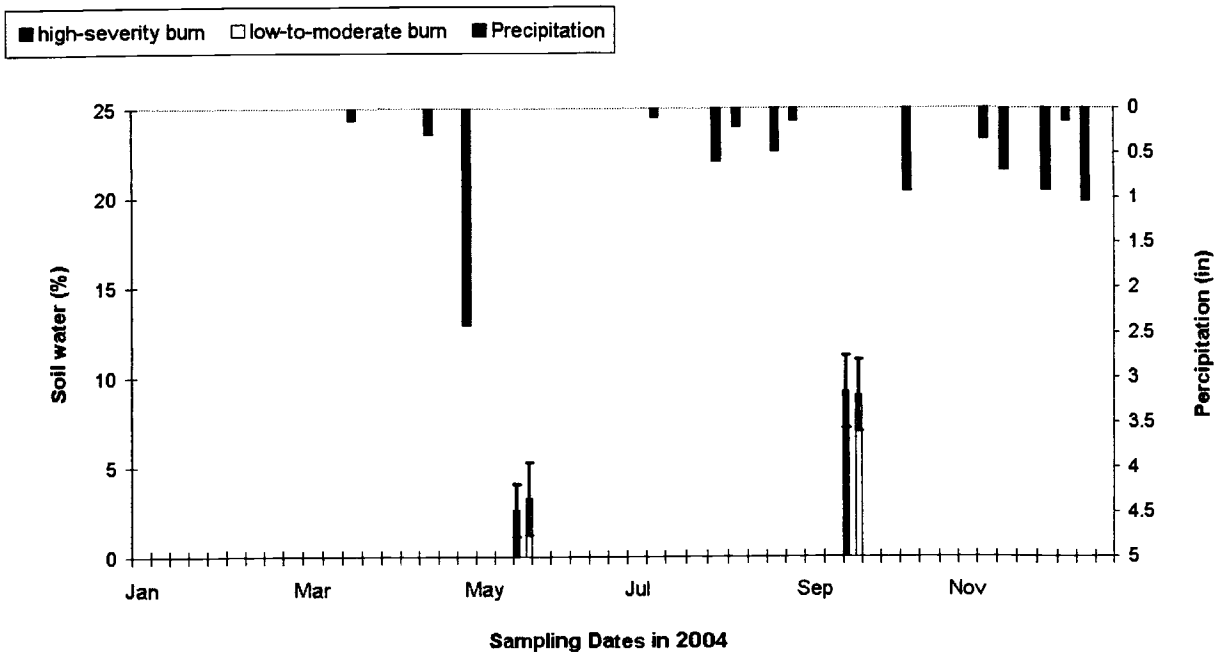


Figure 1. Average soil moisture and 90% confidence intervals (bottom) and precipitation events (top) on the Stermer Ridge watersheds for the three-plus years of post-fire sampling (continued on next page).



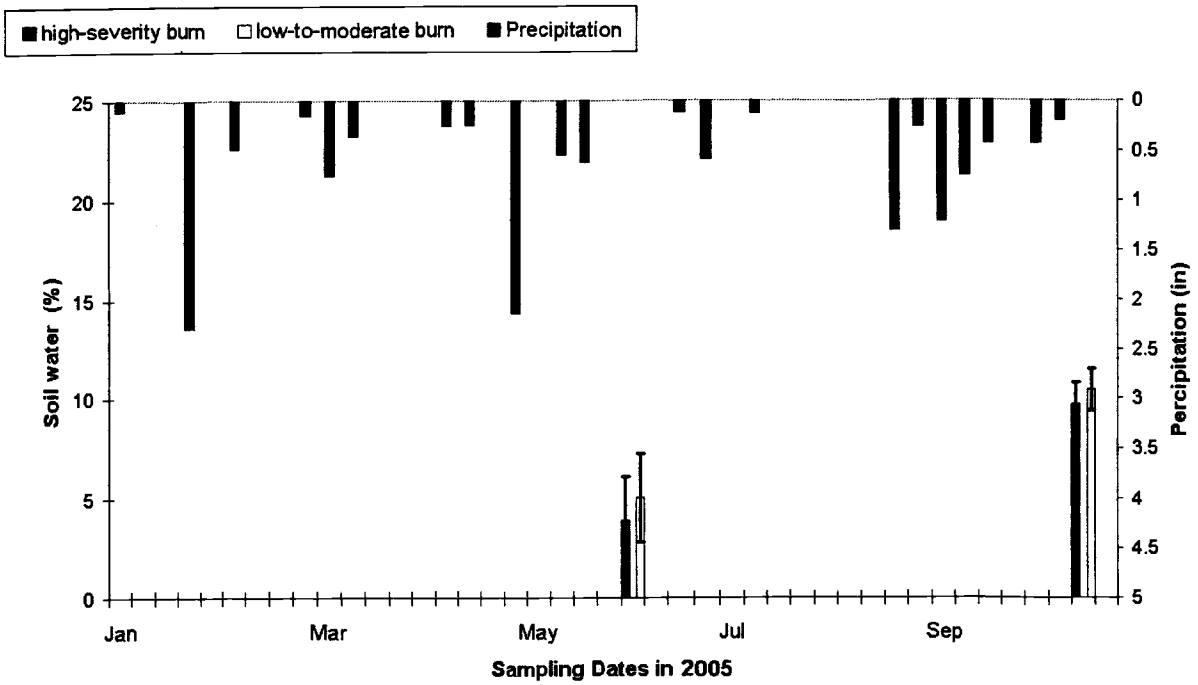


Figure 1 (continued).

THE EFFECTS OF LOGGING BURNED WOOD ON SOIL EROSION RATES

Joe H. Stabenow, Kristin N. Ulvestad, Logan Fitz, Vern Hardee, Greg Howard, Kris McClelland, Melissa A. Robbins, Wendy Woodward, and Fred A. Sundberg[1]

The Rodeo-Chediski fire of June and July 2002 ravaged approximately 462,000 acres of Apache land and Apache-Sitgreaves National Forest in northeast Arizona, igniting a debate on both a local and state level about forest management techniques. Despite the strong opinion of all parties whether or not forests should be thinned, and what should happen to the burned areas, the assumption was voiced that burned areas, if logged, would have significantly higher erosion rates. However, no controlled scientific study until now has been undertaken to definitively measure or compare erosion rates in burned-logged versus burned-unlogged forests. Therefore a study was designed to determine the effects of logging and its consequences on soil erosion in the burned areas of the Rodeo-Chediski fire.

Three types of sites were studied: unburned areas served as a control to measure the natural erosion rates, burned-unlogged areas provided a control for natural erosion rates in high-severity burned areas, and the burned-logged sites provided data on the effects of logging in high-severity burned areas. These sites were chosen on the basis of their similarities in hillside location, original canopy cover, slope (5–13.5°), and drainage area (0.031–0.035 ha).

LOCATION

The study areas are located on the north-central portion of the Rodeo-Chediski burn area in central Arizona. The unburned (UB) sites are located approximately 6 km (3.7 mi) south adjacent to Lons Canyon (NW 1/4, Sec. 13, T10N, R20E). The burned-unlogged (B) and burned-logged (BL) areas are located approximately 2 km (1.25 mi) south of the town of Pinedale on the flanks of Turkey Hill (SE 1/4, Sec. 6, T10N, R19E). In the burned-logged areas, the fences were installed after the burned wood was logged in May of 2004. Sites were selected, however, on a "worst-case scenario" basis, in that the logging damage to the ground was noticeable. BL1 has a road on its upper part, BL2 has a skid path, and BL3 has large ruts in the middle of the drainage area that is evidence of the passage of heavy logging machinery.

METHODS

Silt fences (see Robichaud and Brown 2002) were used to catch sediment runoff. The drainage perimeter and the drainage area were calculated using GIS and slope was measured using a clinometer. Industrial red chalk was spread on the ground to a distance of approximately 60 cm into the drainage area from the silt fence to mark the original ground level. Rain Wise digital electronic rain gauges were installed at or near each silt fence. Rain data were collected with a HOBO and then downloaded using the program BOXCAR.

The line transect method (Wollenhaupt and Pingry, no date; Environmental Protection Agency 1994; Caratti, no date) was used to determine ground cover within each drainage area. Ground cover surveys recorded the amounts of branches, litter, rocks, herbs, shrubs, roots, trees, and bare soil. Ground cover surveys were conducted in October or September of 2003, 2004, and 2005.

Sediment behind the fence was collected generally in April and September of each year. Soil mass was determined with a PESOLA® 35 kg spring scale. A subsample of the soil was collected and air dried for a week to determine the soil's mass and the moisture content. Rates of erosion were based on the amount of sediment moved per hectare over a period of time. Two values are presented: the total amount of sediment moved in a year and the average amount of sediment moved during a month of precipitation. For the amount of sediment moved per year, totals for the summer and winter erosion periods were added together to give kilograms per hectare per year (kg/ha/yr).

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The average amount of sediment moved during periods of precipitation provides information as to when the majority of erosion is taking place and at what rate. The two main precipitation periods in Arizona are winter rains and snows (November to April) and summer monsoons (July to September). Thus, the kilograms per hectare were divided by the months that sediment was collected behind the silt fences.

Bivariate plots were used to compare erosion rates with the variable of interest (percent herb, soil, rock, etc.). Averages of the different types of sites were compared using a simple t-test. The numbers of sites are low (3 each), and the variability within the different types of sites made achieving significance difficult.

RESULTS

Table 1 and Figure 1A show that soil erosion rates for 2004-05 were relatively low in the unburned areas (79.5–356.1 kg/ha), highest in the burned areas (9842.8–27,234.2 kg/ha), and slightly lower in the burned and logged areas (924.2–14,074 kg/ha). The values for the winter of 2003-04 were not used because logging had not yet occurred. Average precipitation was 28.87 inches (733 mm) for the 2004-05 season and 11.85 inches (301 mm) for the 2005-06 season.

Summer erosion rates for 2004 and 2005 showed a similar difference between the burned and unburned sites (Figure 1B; winter erosion rates are not discussed here due to space limitations). The burned sites on average had an erosion rate 32–111 times higher than the unburned sites. Summer 2005 erosion rates for unburned sites decreased to 82.2 percent of the previous summer. The burned-unlogged sites decreased to 32 percent of the previous summer erosion rates. Burned-logged sites decreased to 16.0 percent of the previous summer erosion rates.

The unburned sites had the most vegetation, such as litter, while both the burned-unlogged and burned-logged sites had less vegetation and much more exposed soil (Figure 2). The burned sites had more exposed rocks than the unburned sites due to less vegetation. Litter was the most predominant ground cover in unburned sites, and it increased through the years. The averages for exposed soil decreased. In the burned-unlogged and burned-logged sites the ground cover surveys conducted in 2005 revealed an average increase in litter (5.1%) and herbs (5.7%), as well as a decline in exposed soil (6.5%) and rocks (6.5%).

As mentioned, the climate in the White Mountain area has two rainy seasons: the winter between November and April and the summer monsoons between July and September (Figure 3). The major dry seasons are May–June and October–November. Snow constitutes the majority of winter precipitation, and summer precipitation is largely rain. The summer monsoon season brings higher intensities of rain as opposed to the slow melting of snow during the winter.

Each silt fence site received approximately the same amount of precipitation with only some minor variation. Rainfall was about the same as the historic average in the winter of 2003-04, summer of 2004 (slightly higher in August), and summer of 2005. Rainfall was nearly three times the historic average in the winter of 2004-05. In contrast, rainfall was nearly four times less in the winter of 2005-06, although the recorded amount is probably less due to deep snow (2–3 ft) slumping off the rain gauge in March.

The t-tests of the erosion rates suggest that there are significant differences between all the burned

Table 1. Seasonal and yearly soil erosion rates (kg/ha).

Site	Fall 2004	Summer 2004	Winter 04-05	Total 2004-05	Summer 2005	Winter 05-06	Total 2005-06
UB2	11.1	37.1	31.3	79.5	51	3.4	54.4
UB3	16.3	65.6	6.6	88.5	63.1	5.9	69
UB4	119.1	118.5	118.5	356.1	338.7	25.7	364.4
B1	2283.7	24364	586.5	27234.2	12363.4	508.9	12872.3
B2	1074.7	8808.4	121.8	10004.9	5499.4	130.7	5630.1
B3	845.7	8626.8	370.3	9842.8	4304.4	15.3	4319.7
BL1	1362.7	12569.8	141.7	14074.2	3972.3	164.7	4137
BL2	30.4	889.1	4.7	924.2	23.5	0	23.5
BL3	665.4	6998.6	809.3	8473.3	2922	161.6	3083.6

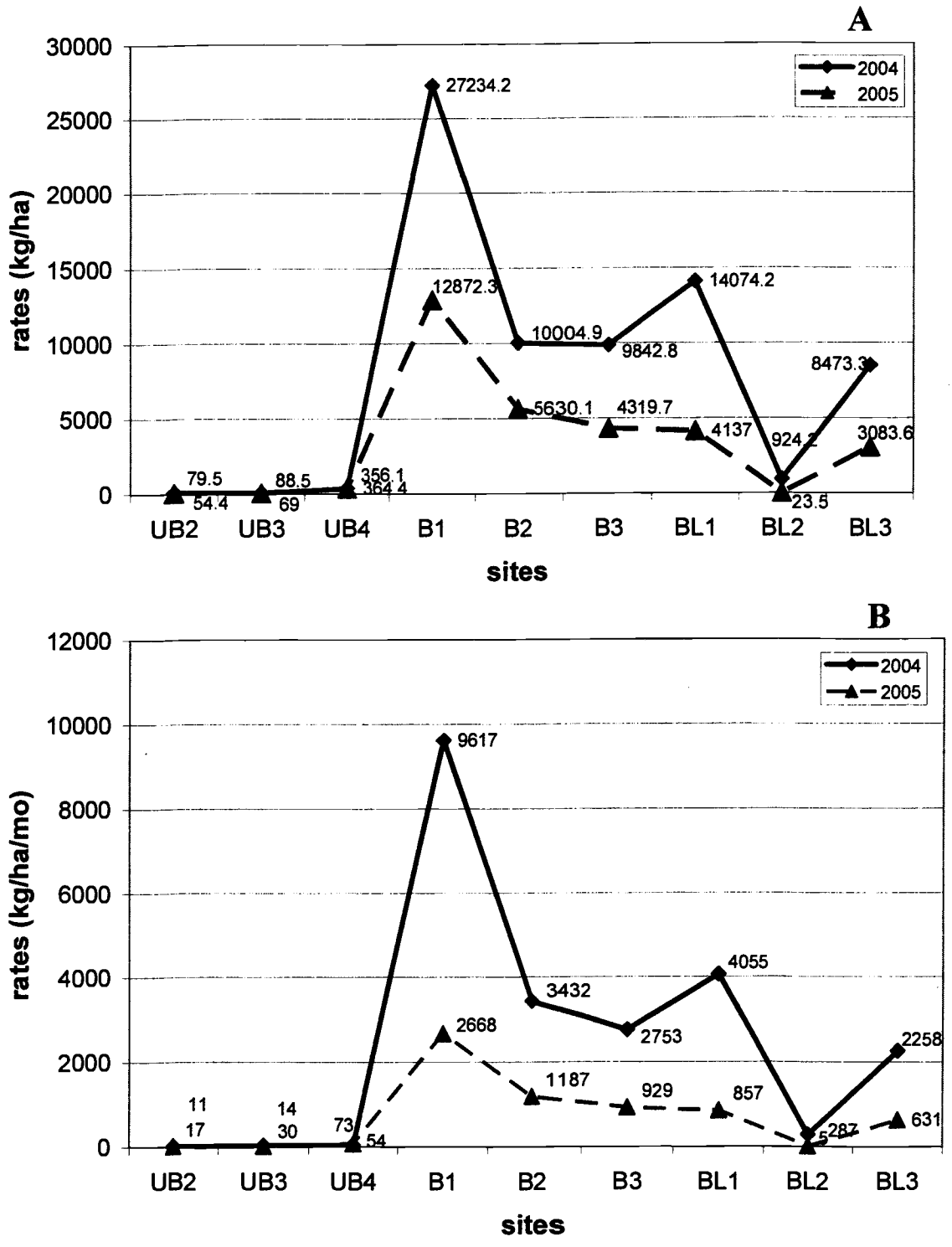

Figure 1. (a) Yearly erosion rates for 2004 (summer to winter 04-05) and 2005 (summer to winter 05-06); (b) summer erosion rates for 2004 and 2005.

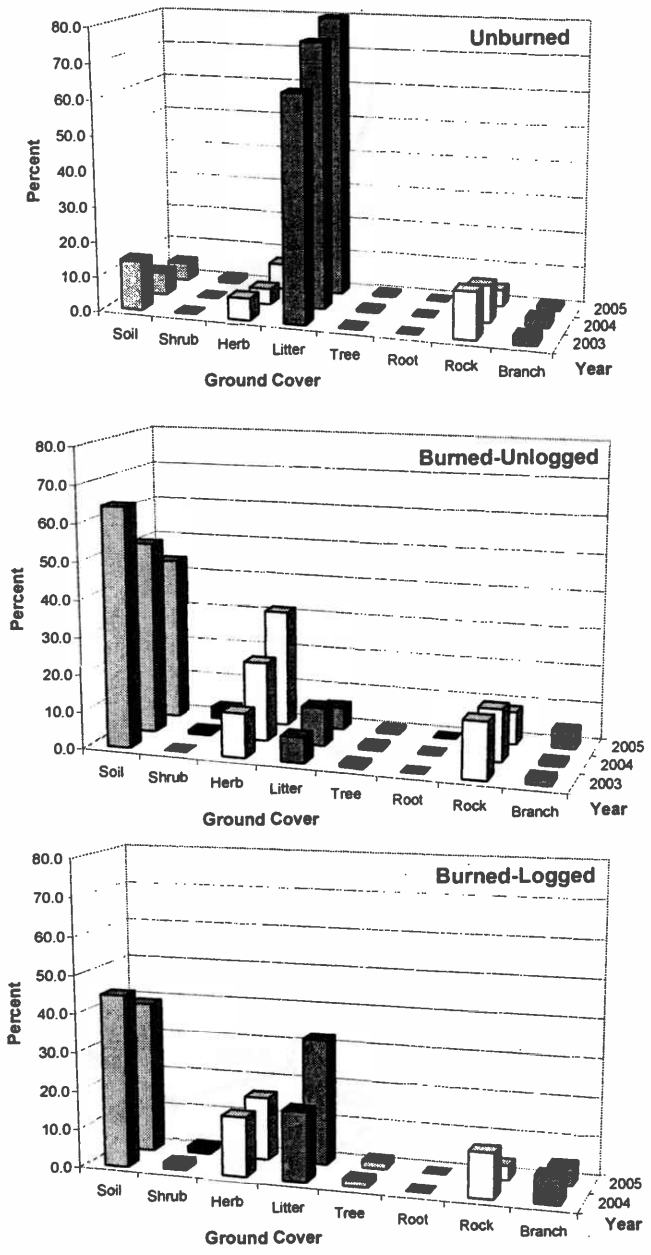

Figure 2. Average yearly changes in ground cover for all study areas.

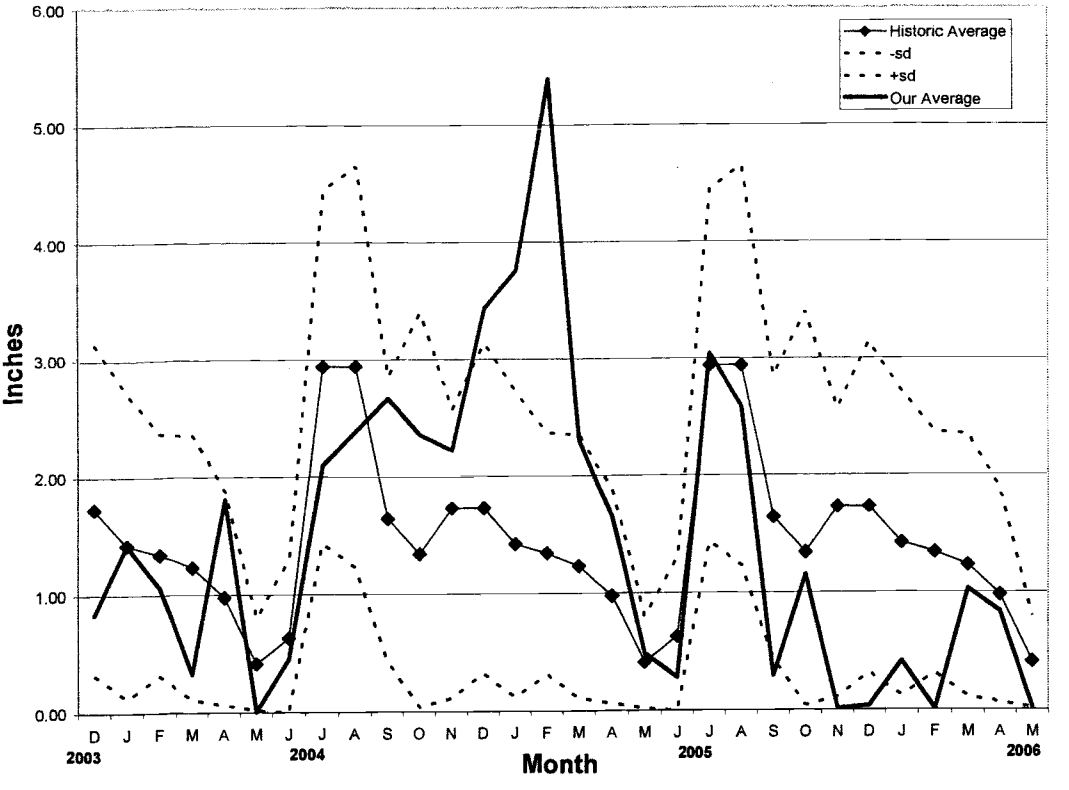

Figure 3. Rainfall during the study period (sd = standard deviation of historical amounts).

areas (B and BL) and the unburned areas (UB) for the summer erosion rates (Table 2). Several differences are obvious between the burned sites and the unburned sites, which may explain the difference in summer erosion rates. The t-test conducted on the major variables (Table 3) illustrates that the amounts of litter, herbs, and soil are significantly different between the burned and unburned sites. In contrast, the burned-unlogged and burned-logged areas had significantly different amounts only of litter in 2004 and only herbs in 2005. Further discussion of the results is limited to only the areas that have been burned-unlogged and burned-logged.

The results discussed here do not include the site B1 which is an outlier in erosion rates (see Figure 1). In addition, ground cover variables are only discussed in relationship to summer erosion rates due to the high values of these rates when compared to winter. Regression analyses of the data for 2004 and 2005 revealed that the soil exposure and herbs + litter variables stood out as major contributors to summer erosion rates (Table 4). As a combined unit, herbs + litter was the most influential ground cover variable, with an R^2 value of 0.6331. Regression analyses illustrate a negative correlation of erosion rates to the percentage of litter and herb cover (Figure 4A). Another important factor is soil exposure, with an R^2 value of 0.6157. There is a strong positive correlation of the percentage of bare soil to erosion rates (Figure 4B). The other ground cover variables have low R^2 values.

Other factors that appear to control the summer erosion rates in the burned areas (B and BL) include slope angle and amount of rain. In 2004, the summer erosion rates showed a strong correlation to hillside slope (Figure 4C); in 2005, the erosion rates showed less of a correlation to hillside slope (Figure 4D). Summer rain decreased in 2005 when compared to 2004. This decrease corresponds to a decrease in erosion rates (Figure 4E).

DISCUSSION

An obvious difference exists in erosion rates between the unburned and burned sites. The most obvious physical difference between these sites is the large amount of litter and the small amount of

Table 2. The *p* values from t-test of erosion rates.

Type of treatment	Winter 2003-04	Winter 2004-05	Summer 2005-6	Summer 2004	Fall 2005	Fall 2004
All burned vs. unburned	0.351	0.074	0.099	0.035	0.038	0.022
Burned-unlogged vs. burned-logged	—*	0.860	0.548	0.299	0.169	0.728

*There are no winter values for burned-logged.

Table 3. The *p* values from t-test of the major ground cover types in the different treatment areas; bold values are significantly different.

Comparison	Branch	Rock	Tree	Litter	Herb	Shrub	Soil
B vs. UB 2003	0.5712	0.8297	0.0480	**0.0010**	0.0571	0.5091	**0.0075**
B vs. UB 2004	0.5982	0.6402	0.2992	**0.0005**	**0.0058**	0.1655	**0.0023**
B vs. UB 2005	**0.0174**	0.6278	0.1208	**0.0002**	**0.0086**	0.5698	**0.0001**
B vs. BL 2004	0.1573	0.8358	0.6004	**0.0343**	0.4123	0.6524	0.6954
B vs. BL 2005	0.9958	0.3452	0.9694	0.0580	**0.0142**	0.3329	0.6026

Table 4. The R^2 values for the different ground cover types vs. erosion rates in the burned-unlogged and burned-logged sites combined for different years and seasons and combined seasons. Site B1 was not included in the regression analysis.

Factor	Winter 03	Winter 04	Winter 03-04	Summer 04	Summer 05	Summer 04-05
Soil	—*	0.0775	0.0369	0.7802	0.5046	0.6157
Herb	—	0.0006	0.0000	0.1933	0.6124	0.0310
Litter	—	0.0490	0.1106	0.4059	0.7421	0.1511
Herb & Litter	—	0.0286	0.0122	0.6706	0.5617	0.6331
Branches	—	0.2381	0.1373	0.0423	0.1195	0.0016
Rocks	—	0.3341	0.3546	0.1987	0.4072	0.0149
Slope	—	0.0204	–	0.9682	0.7023	–

*Only two sites.

bare soil present at the unburned sites (Table 3, Figure 2), which is probably the reason for the difference in erosion rates.

The factor with the most influence on erosion in the burned-unlogged and burned-logged areas was the steepness of slope. Erosion rates seem to have a moderate-high correlation to slope. Previous studies (see DeBano et al. 2005, Table 2.10) have shown that slope strongly influences erosion rates. The erosion rates of the relatively low slopes (8–24%) in the Pinedale study area were 1–27 kg/ha (for the second year), compared to the correspondingly higher erosion rates (first year rates of 72–370 kg/ha; DeBano et al. 2005) of steeper slopes (43–78%). Slope had a lower correlation to erosion rate and a lower slope of the regression line for summer 2005. This decrease is probably the result of the higher increase in correlation in combined percentage of herbs + litter and the decrease in exposed soil at the burned sites.

Other significant factors that influenced the erosion rates in the burned-unlogged and burned-logged areas were ground cover, exposed soil, and rainfall. The increase in ground cover from 2004 to 2005 was probably in part the reason for the decrease in erosion rates during the summer storms. The reduction in erosion rates, however, cannot be clearly attributed to the increase in ground cover. Rainfall during the summer of 2005 amounted to approximately 3 inches, whereas rainfall in the

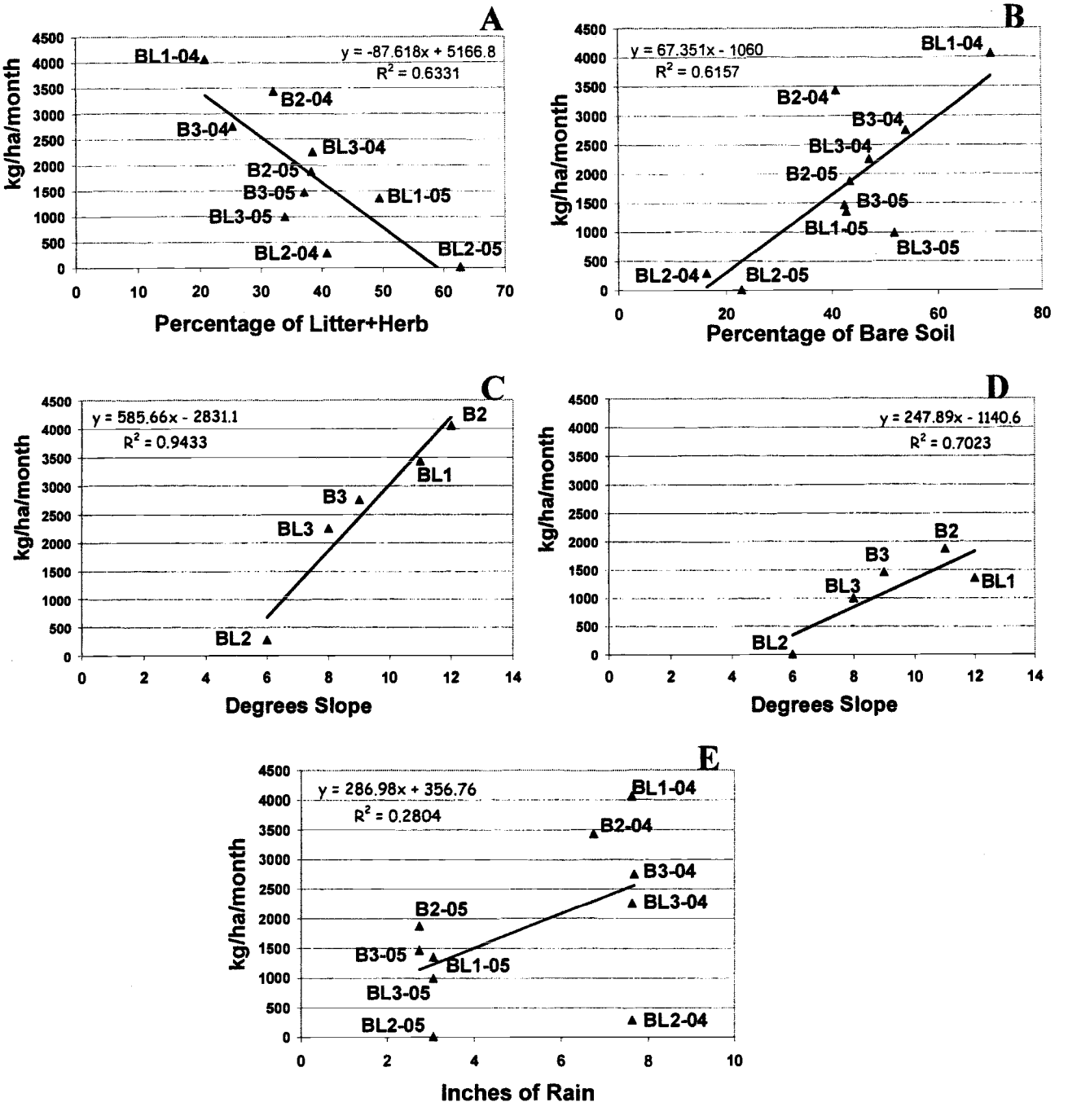

Figure 4. Bivariate plot of the summer erosion rates and the combined percentage of (a) litter and herbs, (b) percent bare soil, (c) slope 2004, (d) slope 2005, and (e) inches of rain in burned-unlogged (B) and burned-logged (BL) areas for 2004 and 2005. Note the lower slope and R^2 values for 2005.

summer of 2004 was about 7.5 inches. Thus the reduction in erosion rates for the summer of 2005 was probably also the result of decreased rainfall.

Site B1 had extreme erosion rates; for example, in the summer of 2004 the erosion rate was 9617 kg/ha/mo. B1 was thus eliminated from the analyses because it is an outlier. The high amount of erosion at B1 may have been due to the amount of rock on the surface.

Comparison of the erosion rates in the Pinedale study area to other areas in Arizona is limited due to the few available comparative studies. DeBano et al. (2005, Tables 2.9 and 2.10) reported first year erosion rates of 0.1–1.3 mg/ha in low- to high-severity wildfire areas in a ponderosa pine forest. These rates are less than either second or third year erosion rates (1–27 kg/ha) in the high-severity burned areas at Pinedale. In contrast, first year erosion rates in chaparral areas are generally higher after wildfires (29–204 kg/ha).

CONCLUSION

Should salvage lumbering be allowed in badly burned areas of national forest, and will this increase the erosion rates in logged areas? Results of this study do not support the hypothesis that erosion rates will change as a result of some types of lumbering activities. Instead, the differences in erosion rates at these sites has been tentatively found to be more closely tied to the slope of the drainage areas, the amount of herbs and litter, and the amount of rocks on the surface.

Limitations of this study included the small number of study sites (3 silt fences erected in each of the three areas—burned-unlogged, burned-logged, and unburned), and the fact that this study was not begun immediately after the 2002 fire, but instead began in 2003. The most significant erosion tends to occur in the first year after the fire. This reduction in erosion, however, can be seen from the erosion rates of 2004 to 2005, but this reduction may be in part due to the reduction in rainfall between the two monsoon seasons.

ACKNOWLEDGMENTS

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RESTORING THE HEALTH OF FIRE-ADAPTED ECOSYSTEMS IN THE SOUTHWEST: SOME EFFECTS ON SOIL AND WATER

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The Sky Islands of southeastern Arizona have a variety of ecosystems ranging from desert scrub to spruce forests (Lefevre 1998). Between these extremes are desert grasslands, oak woodlands, and mixed conifer forests. These are adapted to frequent fires and other disturbances. However, changes in stand structure and species composition within these systems have made many of them unsustainable (Harrington and Sackett 1992; Quinn and Wu 2004). Stand-replacing wildfire and insect attacks have resulted in upland and downstream changes within the sky islands. Recent dramatic changes in the number and size of disturbances are best illustrated with the following statistics. From 1977 through 2000, 17 fires greater than 300 acres required a Burned Area Emergency Response (BAER) action on the Coronado National Forest. The total acreage involved in those fires was about 82,000 acres, an average of 3444 acres per year. Since 2000, 17 additional fires totaling 250,000 acres have required BAER action. Insect activity was at endemic levels during that same period, with an average of 41,106 acres per year. In addition, approximately 12,000 acres of tree mortality due to insect attack were observed from 1975 through 2000. Since 2000, tree mortality due to insect attack in the sky islands has totaled more than 36,000 acres. Actions being taken in response to these changes in size and number of disturbances are part of the Southwestern Region of the Forest Service Central Priority: Restore Fire-Adapted Ecosystems. The details include larger programs to thin stands through mechanical means and broadcast burning, fuel reduction by piling and burning and increased sales of forest products, and mechanized removal of woody material to off-site locations. These activities have long been recognized as having impacts on watershed conditions (Wisler and Brater 1949; Hewlett 1969; McDonald et al. 1977; Page-Dumroese et al. 2006), not too unlike the impacts of wildfire and insect attack.

A BRIEF BACKGROUND TO UNDERSTAND THE NEGATIVE EFFECTS

Soil

Approximately 500,000 acres of the forest have been assessed for soil quality; 83 percent of the area is found to have satisfactory soil conditions. Acreage found to be in impaired or unsatisfactory conditions is rated in those categories generally because the plant community has changed to one that does not resist erosion or cycle nutrients as effectively as the potential natural community. Introducing fire into these areas could promote a change toward the desired community.

While fire is happening, soil is heated, changing some characteristics. Most organisms living in the soil die when soil temperature is raised to near 100° C. Water repellency (hydrophobicity) is increased if soil containing organic matter or covered with organic matter is heated between 176 and 204° C. This occurs as organic substances are vaporized and then condensed as they leach downward into cooler layers of mineral soil, generally within 5 cm of the surface. Complete deydration of the soil occurs when it is heated beyond 220° C, but this alone does not change any physical characteristics. Soil structure is altered if the soil is heated beyond 460° C, which is a rare occurrence. Soil erosion increases when the organic matter protecting it is burned off, hydrophobicity increases, and structure changes. Mass movements such as landslides can also occur (DeBano et al. 1998).

Compaction occurs with the use of heavy equipment such as trucks, skidders, loaders, and bulldozers. This can lead to increased bulk density,

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restricted root growth, decreased water infiltration and porosity, and more erosion (Page-Dumroese et al. 2006). These changes reduce productivity and consequently ecosystem sustainability.

Riparian

Riparian areas are those that have soil characteristics or distinctive vegetation communities that require free or unbound water. Following fires there will be more water, more sediment, and more nutrients flowing from the burned area (Baker 1988). Even in cases where the increases are within prescribed standards, unsatisfactory riparian areas can be damaged by large quantities of water or sediment. Healthy riparian areas are able to function and thrive through variations in water and sediment up to approximately 25-year events (DeBano and Schmidt 1989). Events exceeding this level can result in removal of all trees with the exception of the largest riparian specimens, restructuring of the channel shape, and change in size distribution of substrate.

Operating heavy equipment in the riparian area or the watershed contributing to the riparian area can reduce riparian area sustainability (Dahms and Geils 1997).

Watershed Condition

The initial effects of changes to watershed conditions may cause erosion, sedimentation, and channel alterations that are unacceptable to plan objectives. The benefits only arise after sustainable ground cover has become reestablished and maintained. The overall effects of introducing fire will be beneficial to watershed conditions and will thus enable land managers to sustain satisfactory watershed conditions.

Watershed condition results from the integrated effects of hydrologic function and soil productivity. Watersheds in good condition exhibit the following qualities (Debano et al. 1998):

- Precipitation infiltrates into the soil.
- Precipitation does not contribute excessively to erosion.
- Streamflow response to precipitation is relatively slow.
- Baseflow is sustained between storms.

When a watershed burns, fire affects watershed condition in the following ways:

- Reduced interception – the burning of vegetation and litter reduces precipitation interception, allowing more precipitation to strike the soil surface directly.
- Reduced evapotranspiration – burned vegetation converts less precipitation into water vapor, leaving more water available for runoff.
- Reduced infiltration – burning vegetation and litter reduces infiltration of precipitation into the soil, resulting in more water available for runoff.
- Increased soil water storage – decreased evapotranspiration can result in more water storage at the end of the growing season, leaving the watershed more responsive to subsequent precipitation events.
- Increased runoff – the factors cited above all promote higher levels of runoff after a fire, which in turn increases erosion and affects the rate of recovery.
- Increased streamflow – reduced evapotranspiration will result in increased streamflow, which in turn affects channels.

In an area that has had fire excluded for an extended period of time, interception, evapotranspiration, infiltration, soil water storage, runoff, and streamflow may all be performing in an unnatural way, and introducing fire will change them. The initial effects of such changes may be visible as erosion, sedimentation, and channel alterations that are outside the natural range of variability if areas burned are too large or too severely burned. The overall effects of introducing fire will be beneficial.

Sediment transport is an important aspect of water quantity and quality that should be considered when planning a prescribed burn. Fires that burn intensely enough to consume large portions of the protective litter on the soil surface leave behind a watershed that will produce a large amount of sediment. Because sediment yield occurs in pulses depending upon precipitation events, some burned areas produce much greater increases in sediment than others. Prescribed fires generally result in less total sediment increase than wildfires because prescribed fires do not burn as much of the litter as wildfires.

Negative effects of wildfire include infrastructure damage by burning and post-fire erosion and flooding (DeBano et al. 1998; Taylor 1988); erosion and consequent changes in site productivity and downstream aquatic habitats (Rinne and Neary 1996; DeBano and Neary 1996; DeBano et al. 1998;

Garcia-Chevesich et al. 2004; Neary et al. 1998); the death of large trees which are prized for recreation areas and essential for many species of wildlife (Zwolinski 1996; Harrington and Sackett 1992; Quinn and Wu 2004); and the diversion of management efforts from desired programs such as recreation and education to emergency responses.

Negative effects of fuel reduction by thinning mechanically or selling products can also include erosion and consequent changes in productivity and downstream aquatic habitats, removal of trees (rarely large), and diversion of management efforts (Wisler and Brater 1949; Hewlett 1969; McDonald et al. 1977; Page-Dumroese et al. 2006).

The potential for aggressive non-native plant species to occupy the disturbed sites is a new problem land managers have to solve. This situation may occur in all projects that open up stands of trees or brush, or disturb soil.

ACTIONS PROPOSED TO RESTORE ECOSYSTEMS

In the years leading up to 2005, the Coronado National Forest conducted a variety of projects with the objective of improving or maintaining range and forest habitat types. Most of these projects were in response to an identified discrepancy between existing conditions on the ground and desired conditions as described in the Forest Plan. Examples would be soil ripping to counter compaction on rangelands, mesquite pushing to reduce the encroachment of trees into grasslands, fencing riparian areas to keep cattle and vehicles from damaging channel banks and vegetation, gully plugs or headcut drop structures to stop the advance of gully systems, prescribed fires to reduce stand densities or create openings for wildlife habitat, and thinning or sanitation cuts to reduce the impacts of insect attack in timber stands.

In the pre-2005 projects, some of the material was removed in the form of firewood or other low-value products, and some products were offered in response to demand from the public. In all, about 200 acres of land were treated annually through product sales, and an additional 110 acres were treated with machinery with the objective of improved watershed condition or range condition. Prescribed burning varied greatly due to weather constraints, but 13,000 acres per year was not uncommon. Wildfires, as indicated above, were fought vigorously and averaged about 3400 acres per year until 2000. Unfortunately, wildfire burns averaged more than 41,000 acres per year between 2000 and 2005.

The plans for the next 10 years are to increase activity in the mechanical treatment and product harvest. Because there is a lack of both access and market for most of the products, prescribed burning will be concentrated in those areas, often at great cost. Land treatments are planned to affect about 550 acres per year, and product harvest is projected to affect an additional 250 acres per year. Prescribed burning is projected to treat about 5000 acres per year. This indicates a total treatment area of about 5800 acres per year with specific objectives for restoring fire-adapted ecosystems. Watershed and range condition maintenance and improvement are expected to occur on these acres as well.

EXAMPLES OF PROJECTS DESIGNED TO RESTORE THE HEALTH OF FIRE-ADAPTED ECOSYSTEMS IN THE SOUTHWEST

The Pinaleno Ecosystem Management Project involves 1100 acres in mixed conifer forest where stands are being thinned from below (no trees larger than 9 inches dbh will be cut) and the stems are piled and burned or offered as products. No heavy equipment is proposed for use off of established roads. Positive effects include reduced opportunity for torching from ground fire to crowns of mature trees. Negative effects are removal of stored carbon from the site and soil heating beneath the piles.

The San Rafael Manzanita Project involves 1000 acres in oak woodland habitat in which manzanita plants are being removed by mastication with a Brush Hog machine. Positive effects are reduced heat from fire and less opportunity for torching from ground fire to crowns of mature oaks. Negative effects are compaction of the soil by the rubber-tired Brush Hog and the potential for exotic species to occupy the site.

The Rose Canyon Thinning Project covers 300 acres in transition coniferous forest where trees up to 16 inches in diameter are being removed and either offered as products or piled and burned. Positive effects are opening of the stand for potential tree regeneration of most desired species, removal of fire-killed or damaged trees for safety of recreationists, and reduced potential for torching from ground fire to crowns of mature trees. Negative effects include compaction from skidders, carbon removed from the site, and soil heating beneath the piles.

The Potrero Fuel Reduction Project involves 3500 acres in which mesquite trees are being up-

rooted with heavy equipment. The boles are being offered as firewood, the unusable stems are being piled for burning, and the smallest branches are being lopped and scattered. Positive effects are the reduction of the possibility of catastrophic wildfire by creating defensible space, removing aerial fuels, and removing concentrations of heavy fuels near the Meadow Hills subdivision of the city of Nogales. Negative effects include some compaction from the equipment, carbon removed from the site, and soil heating beneath the piles.

The Johnson Peak Prescribed Fire involves 8000 acres where transition coniferous forest and mixed conifer forest was burned in the fall and winter to reduce fuels of all sizes. Positive effects include encouraging a mosaic of vegetation age classes on the landscape and providing an opportunity to allow natural ignitions to burn in the future. Negative effects include soil heating and vegetation removal where accelerated erosion will occur for a short time.

CONCLUSIONS

Implementing the Forest Service Regional Central Priority to restore fire-adapted ecosystems will have a cost to the land. Heavy equipment will be working on roughly five times the number of acres compared to previous protocol. Prescribed burning will be expensive and weather-dependent. Product sales will result in carbon removal and consequent nutrient cycling alteration. Plant communities will be altered, and the threat of exotic species will be high. In addition, funding for watershed, range, and recreation programs will be reduced or kept flat. However, the expected benefit of making ecosystems sustainable, especially in light of the more than 250,000 acres that have burned uncontrolled in the past 5 years, is very great. Soil erosion can be maintained at or near natural levels through the use of best management practices. Prescribed burning can be accomplished with few effects from soil heating and vegetation damage because burning can be done under conditions that result in cooler fires. Watersheds and rangelands that are sustainable in the face of natural variations in climate, fire, and insect attack can be managed effectively. Recreation areas that are defensible against wildfire or insect attack will remain to meet the demands of both the present and future.

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HYDROLOGIC EFFECTS OF WILDFIRE

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The effect of forest fires on water, especially surface water quantity and quality, is an important topic because surface water constitutes the main source of water for most domestic, industrial, and commercial uses in the United States. The bulk of the surface water is the product of runoff from precipitation that falls as snow or rain on our forested and rangeland watersheds. In many areas, such as the arid and semi-arid Southwest, the vegetation in these watersheds is dry and susceptible to wildfires. Oftentimes fire in the form of prescribed burning is used to protect these areas from wildfire. However, such fire suppressions have resulted in overcrowded vegetation and the production of abundant fuels in watersheds.

Dense vegetation and frequently recurring drought conditions across the country in general, and in the Southwest in particular, have led to numerous catastrophic fires that have scorched many of the nation's forests, rangelands, parks, and other large-scale real estate properties. For example, 77,534 fire incidents burned 6,790,692 acres in the United States in 2004. These burns have tremendous effects on the characteristics of water-producing watersheds and the quantity and quality of the water coming out of them.

GENERAL WILDFIRE EFFECTS

In the past few years, the western part of the United States has seen dramatic increases in the number and intensity of wildfires, which cause enormous damages to forests, rangelands, and other rural areas. In the year 2004 alone, for example, five federal agencies—the Bureau of Land Management, the Bureau of Indian Affairs, the Fish and Wildlife Service, the National Park Service, and the Forest Service—together spent $890,233,000 suppressing wildfires nationwide. The same activity cost the agencies $1,326,138,000 and $1,661,314,000 in 2003 and 2002, respectively. These costs, though very large, do not include any monetary and material expenditures by other federal, state, or local governmental agencies and private sources. State land departments, fire fighters in rural and urban communities, and land managers also spend substantial amounts of money and materials to suppress local wildfires.

There have been very large fires close to home in Arizona recently, which cost the state very much in terms of financial, environmental, and other valuable resources. In June 2005, one fire—the Cave Creek Complex fire—burned 248,310 acres of forest, pasture land, and private property all over central Arizona. That fire, which was the second largest fire in Arizona's history, cost $16,471,000 to suppress. The largest fire in state history was the Rodeo-Chediski fire, which burned 468,638 acres and destroyed 491 structures in the White Mountain area of Arizona in 2002. That fire was a part of 6.7 million acres of forest and wildlife habitat area burned in the United States in that year. Such large fires have many damaging effects, some immediate and others delayed, on the environment. At the time of burning, numerous valuable land resources such as timber, wildlife and wildlife habitat, understory vegetation, soil and soil chemicals, historical artifacts, and residential homes are immediately either damaged or destroyed. The delayed effects include numerous forms of post-fire environmental degradation, such as loss of vegetation cover which leaves land exposed to impacts from rainfall, runoff, wind, and solar radiation, resulting in soil hydrophobicity (DeBano et al. 1998), flooding, soil erosion, and off-site downstream degradation of streams, lakes, and reservoirs (Morgan and Erickson 1995; Veenhuis 2002). Knowledge and good understanding of these possibilities is important for developing appropriate forest and other landscape management techniques to minimize wildfire's effects on water.

EFFECTS ON WATER YIELD AND PEAKFLOW

The main concern for hydrologists and water resource managers is the impact wildfires have on

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water quantity and quality. The amount of vegetation cover influences not only the amount of precipitation reaching the ground but also the amount of water infiltrating into the ground and moving along the surface. The presence of vegetation decreases water yield by intercepting precipitation, enhancing infiltration rate, and slowing surface movement. Wildfire, on the other hand, not only burns vegetation cover but also destroys forest floor material, leaving the ground bare and sometimes with hydrophobic soils that slow the infiltration rate and allow for more and faster surface water movement (DeBano 1981; Morgan and Erickson 1995; Zwolinski 2000). However, soil hydrophobicity disappears when the temperature of the burned area reaches 300° C. For most fire burns, soil temperatures remain below this level, leading to hydrophobicity and a subsequent increase in water yield (Dlapa et al. 2006). But the factors affecting water yield are more complex and vary significantly from place to place, depending on rates of precipitation and evapotranspiration, type of soil, and vegetation cover, as well as geology, topography, vegetation type, and fire severity (Robichaud et al. 2000). The increase in water yield also changes with time following fire disturbance. In general, Hibbert (1971) and Hibbert et al. (1982) found that first-year water yield from various burned watersheds in Arizona increases from as little as 12 percent to more than 1400 percent of normal flow.

The effects of fires on storm peak flows are complex and highly variable, as shown in Table 1. The magnitude and the variability of peak flows are dependent on many factors, such as topography, soil and vegetation characteristics, fire severity, and precipitation intensity. Peak flows over burned areas in the Southwest commonly increase in magnitude from 500 to 9600 percent (see Table 1) of that occurring on unburned areas during the summer months when highly intensive monsoonal thunderstorms are the norm in the area. Peak flow on the Salt River increased by a very significant 4000 percent after the year 2002 Rodeo-Chediski fire (Figure 1). However, other researchers (Sinclair and Hamilton 1955; Glendening et al. 1961) have found that the increase could be even higher from a burned chaparral watershed (see Table 1); the increase in peak flow from burned chaparral watersheds can reach as much as 45,000 percent. These results reaffirm the need for careful management of Southwestern watersheds to minimize the occurrence of severe wildfires that upset the normal quality and quantity of water supply in the area.

EFFECT ON WATER QUALITY

Similar to effects on water quantity, the influence of wildfires on water quality can be substantial depending on the severity of the wildfire and the physical and chemical characteristics of the burned area (DeBano et al. 1998). Large and fast streamflows from burned areas can pick up and transport large amounts of debris and chemicals that significantly affect the quality and use of water downstream. The most obvious effects come in the form of bedload and suspended sediments in the streamflow, but substantial changes in the amounts of anions and cations can also occur. Table 2 shows the effects of the Rodeo-Chediski fire on water quality compared to safe drinking water parameters. The values in Table 2 are from samples taken from Roosevelt Lake in the Salt River system immediately following the Rodeo-Chediski fire. These very high values are dangerous to aquatic life and other living things. For example, the turbidity value of 51,000 NTU, if it persisted, would make the reservoir water nontransparent and practically too dark for any aquatic organism to function properly. Likewise,

Table 1. Percent increase in peak flow following forest burn at different locations.

Location	Vegetation Type	Percent Increase	References
Eastern Oregon	Ponderosa pine	45	Anderson et al. 1976
Central Arizona	Mixed conifer	500–1500	Rich 1962
Central Arizona	Ponderosa pine	9600	Anderson et al. 1976
Cape region of South Africa	Monterey pine	290	Scott 1993
Southwestern United States	Chaparral	200–45,000	Sinclair and Hamilton 1955; Glendening et al. 1961
Northern Arizona	Ponderosa pine	200–5000	Leao 2005

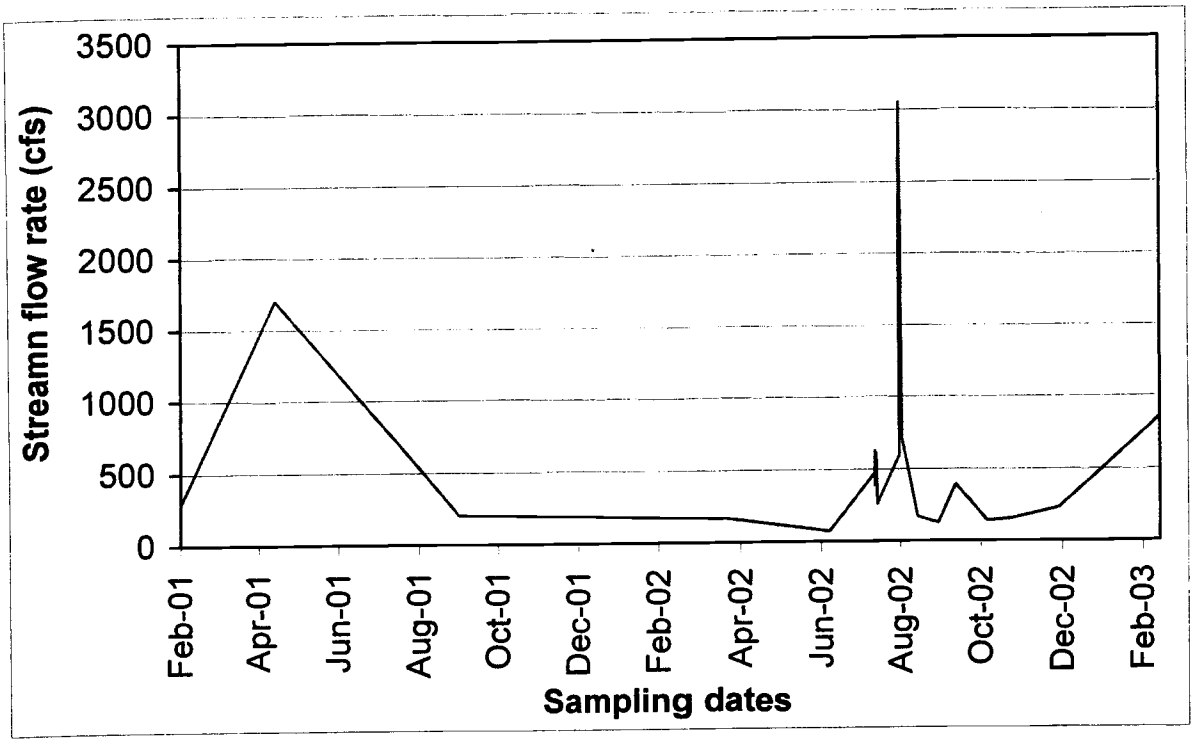

Figure 1. Salt River flow rate at entrance to Roosevelt Lake following the Rodeo-Chediski fire in 2002.

Table 2. Effect of Rodeo-Chediski fire on Roosevelt Lake water quality.

Water Quality Parameter	Post-Fire Values	Secondary Drinking Water Standard
Arsenic	685 mg/L	0.05 mg/L
Bicarbonate	312 mg/L	380 mg/L
Calcium	144 mg/L	50 mg/L
Chloride	2110 mg/L	250 mg/L
Copper	375 mg/L	1 mg/L
Iron	90,600 mg/L	0.3 mg/L
Lead	690 mg/L	0.05 mg/L
Magnesium	45 mg/L	20 mg/L
Phosphorus*	39 mg/L	0.1 mg/L
Potassium	26 mg/L	5 mg/L
Sulfate	170 mg/L	100 mg/L
Total nitrogen	220 mg/L	10 mg/L
Dissolved oxygen	7.4 mg/L	> 5 mg/L
Suspended sediment	25,800 mg/L	500 mg/L
Specific conductivity	6970 µs/cm	1650 µs/cm
Temperature	29° C	
pH	0.1	6.5–8.5
Turbidity	51,000 NTU	(monthly average) 1 NTU (average for 2 days) 5 NTU

*Phosphorus in elemental form for marine animals.
**µs = microsiemens.

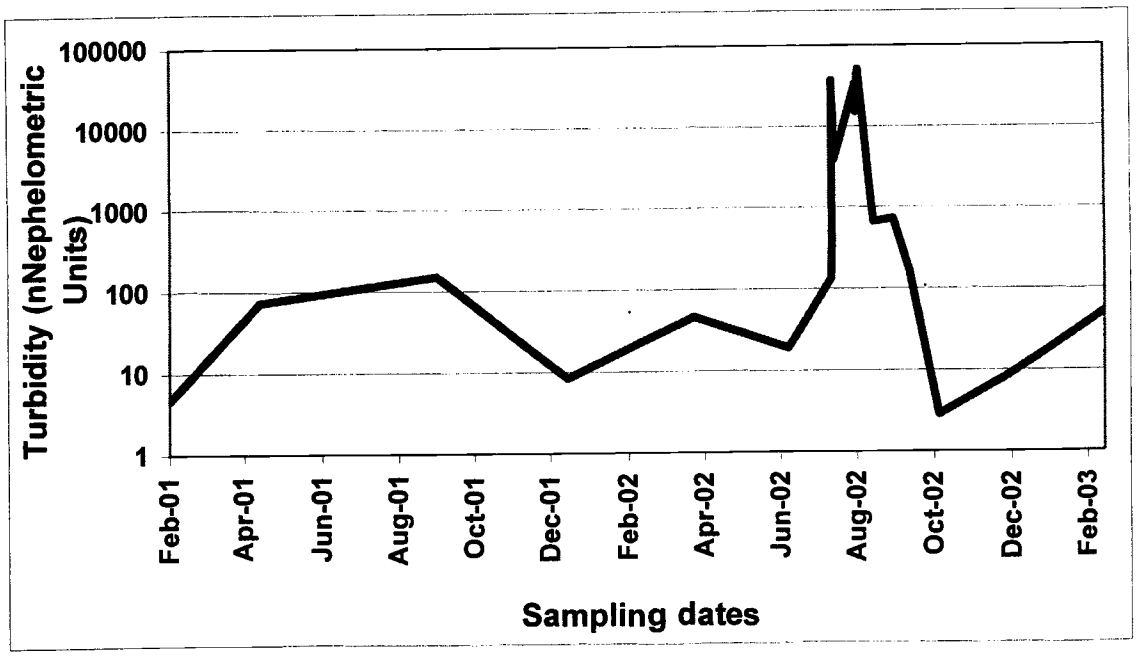

Figure 2. Turbidity of Salt River water at entrance to Roosevelt Lake immediately after the Rodeo-Chediski fire.

the high temperature and low pH values as well as the highly elevated presence of salts and other chemicals would make the water unsuitable for many organisms if the situation had persisted for a long time. The very high macro- and micronutrient values would also lead to increased algal growth and eutrophication of the water, making it unsuitable for drinking. Luckily, the serious effect of the fire on the various water quality parameters did not persist long (Paterson et al. 2002; Wondzell and King 2003). This is demonstrated in Figure 2, which shows a rapid decrease in the turbidity of Salt River water at the entrance to Roosevelt Lake shortly after the burn period.

CONCLUSION

The impacts of wildfires on water and water quality are varied and significant. Because there are insufficient amounts of vegetation cover on watersheds after wildfire burns, most precipitation that falls on such areas is readily converted to surface flow, which moves downstream with little or no difficulty. However, high precipitation over severely burned and unmanaged watersheds may produce large and rapid flows that can carry large quantities of sediment and other chemical contaminants downstream. Hence, it is important that foresters, land resource managers, and any other interested parties make all efforts to minimize the occurrence of damaging fires. This can be done through forest thinning and appropriate harvesting methods, prescribed fire, and paying careful attention to possible occurrences of fires and other hazardous disturbances and dealing with them diligently before they become out of hand. This requires insightful legislation and availability of the budgetary and other resources that are essential for prevention of catastrophic fire. Such proper management of watersheds may produce the right amount of good quality water yield for use by humans, plants, and wildlife.

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A NEW SENSITIVITY ANALYSIS FRAMEWORK FOR MODEL EVALUATION AND IMPROVEMENT USING A CASE STUDY OF THE RANGELAND HYDROLOGY MODEL

H. Wei, M. A. Nearing, and J. J. Stone[1]

Many numerical models involve utilization of a large number of input parameters, which often results in complex interactions between inputs and algorithms within the model. In all models it is generally desirable to understand the relationships between the sensitivity of outputs on input parameter values and how these relationships affect model predictions. This is important not only for gaining a better understanding of the model behavior, but also for detecting model deficiencies and unreasonable responses induced by the high level of model complexity and the high number of model input factors.

Sensitivity analysis (SA) is a method widely used to ascertain simulation model response to changes in its input factors. In practice, SA is not only applied to examine the importance of input parameters but is also considered as an important element of the model development process. SA helps to elucidate the impact of different model structures, to prepare for model parameterization, and to direct research priorities by focusing on the parameters that contribute greatest to uncertainty in the model response (Saltelli and Campolongo 2000; Breshears et al. 1992).

The objective of this paper is to provide a new local sensitivity analysis framework that can be used to effectively show the interdependencies of sensitivity to multiple model inputs, and which can be used in the model development process to help identify undesirable or illogical model responses. We used an algorithm similar to the Morris framework, but a different local sensitivity index to build a localized sensitivity matrix for a model. The sensitivity matrix was further analyzed to make SA more effective as an aid in the model development process. We illustrate the use of this framework to (1) examine the distribution of the sensitivity to each parameter, and thus to list and classify the importance of input parameters; (2) decompose the dependency of model response on input parameter values and understand the parameter interactions, using correlations and regressions; and (3) reveal the nonlinear relationships, thresholds, and potential weaknesses or problems of model structure.

We applied our new method to the Rangeland Hydrology and Erosion Model (RHEM), which was developed from the Water Erosion Prediction Project model (Flanagan and Nearing 1995; Nearing et al. 1989; Laflen et al. 1997). Several local SA tests have been conducted on WEPP (Baffaut et al. 1997; Tiscareno-Lopez et al. 1994). These previous studies were based on site-specific data and parameter values, and the results could not be extrapolated to other locations. This paper, taking the erosion predictions in RHEM as an example, not only highlights the local sensitivities but also describes how to investigate the interactions between RHEM parameters and how to identify unusual RHEM behavior. Results from this study will be helpful in improving the understanding of the model behavior and parameter interactions in RHEM, and also in improving the integrity of the model predictions.

METHODOLOGY

Sensitivity Equation

The local sensitivity index in this paper is quantified by equation 1:

$$S_{i_{(x^0)}} = \frac{\left(Y\left(x_1^0,\ldots,x_1^0+\partial x_i,\ldots,x_1^0\right)-Y\left(x^0\right)\right)/Y\left(x^0\right)}{\partial x_i / x_1^0} \quad (1)$$

where $S_{i_{(x^0)}}$ is the sensitivity of output Y to the input factor x_i at the point of $x^0\left(x_1^0,\ldots,x_i^0,\ldots,x_1^0\right)$. $S_{i_{(x^0)}}$ is a non-dimensional, localized index that represents the normalized response of output to the increase of the input value x_i. The absolute

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magnitude of $S_{i(x^o)}$ indicates the degree of sensitivity of Y to x_i at the point of x^0. A positive (negative) S_i indicates the positive (negative) relationship between Y and x_i; that is, the increase of x_i will cause the increase (decrease) in Y. The percentage of $\partial x_i / x_i^0$ is expected to be small enough to ensure the S_i to be representative at the point x^0. One of the merits of equation 1 is that if $\partial x_i / x_i^0$ remains a constant percentage, the value of $S_{i(x^o)}$ can be used to compare the sensitivity to an input variable at its different magnitudes. It can also be used to compare the sensitivity of output to different individual input factors, for example the sensitivity of Y to x_i and x_j at the point of x^0.

Procedure

Figure 1 is a flow chart of our methodology. It starts with selecting the input and output parameters to be analyzed. The ranges of each input parameter should then be given to build the parameter space of interest, which could encompass the full realistic range of all input parameters. Then points, x^0, were randomly selected from the parameter space, and sensitivity indices were calculated for each parameter at the selected point. The Latin hypercube sampling (LH) method (McKay et al. 1979) was used for random sampling of points, x^0. At each point selected by LH, the model was executed $(1 + I)$ times. The first run was to calculate and save the output value at the point x^0 with no perturbation, and the next I times were to calculate new output values after increasing each parameter, one at a time, by a predetermined percentage ($\partial x_i / x_i^0$). The local sensitivity index for each input parameter at the point was then calculated using equation 2 based on the $(1+ I)$ values of the output at this point. The sampling procedure and local sensitivity index calculation were repeated 10,000 times, after which the parameter space was well covered and points were well distributed. At the conclusion of the runs a sensitivity index matrix had been constructed from the results, containing the values of each parameter at each selected point and the local sensitivity of output to each input parameter at each point. The absolute values of the sensitivities were also generated for further analysis. A FORTRAN program was written to connect the model, LH sampling, the sensitivity loops, and the building of the sensitivity matrix.

Model RHEM and Input Parameter Space

We selected 14 input parameters used in the hydrology and erosion components of RHEM for the sensitivity analysis. *Soil loss* (kg/m^2), the amount of soil erosion from the hillslope, was selected as the targeted output variable. The parameter space of interest for this study is the entire applicable space of the RHEM model. Thus the full range of reasonable parameter values for each input variable was used to build a 14-dimensional parameter space. The sources of the ranges came from the recommendations in the WEPP model manual (Flanagan and Nearing 1995) and WEPP database (unpublished data, personal communication; see Table 1).

Table 1 gives the name, range, and descriptions of each input parameter studied. The range of each input parameter was required for the sensitivity study. The increment of each input parameter and the total number of samples were also required for the SA program. The increment was arbitrarily set at 5 percent in this study. A small value of the increment is preferred to make the sensitivity index representative of the exact localized effect, but it must be large enough to avoid rounding errors in the calculations. The total number of points should be determined by considering not only the number of input parameters but also the complexity of the model. We used 10,000 points in this study as a representative sampling of the full input parameter space.

RESULTS

Approximately 50 percent of the total 10,000 events did not generate rainfall excess, which means that runoff and erosion from these events was zero, and approximately 20 percent of the total events yielded runoff of less than 5 mm, which was considered to be too small to be of interest in terms of output. As a result, only the 3180 of the 10,000 simulated events that generated runoff greater than 5 mm were saved in the sensitivity matrix for further analysis.

Localized Sensitivity

Absolute local sensitivity can be used to compare the relative importance of the input factors. Each row of the sensitivity matrix generates a ranking of parameter importance based on the rank of the absolute sensitivity values at each point. However, the importance of a factor varied from point to point. For example, at point 23, the ranking of sensitive parameters was *rain, dur, ke, ns, xip, ki, sln, psd, slp, fe, fr, rsp, kr,* τ_c. At point 30, the ranking was *psd, rain, dur, xip, ke, ki, ns, slp, fe, sln, fr, rsp, kr,* τ_c. Figure 2 gives lists of the four most important factors based on the count of the

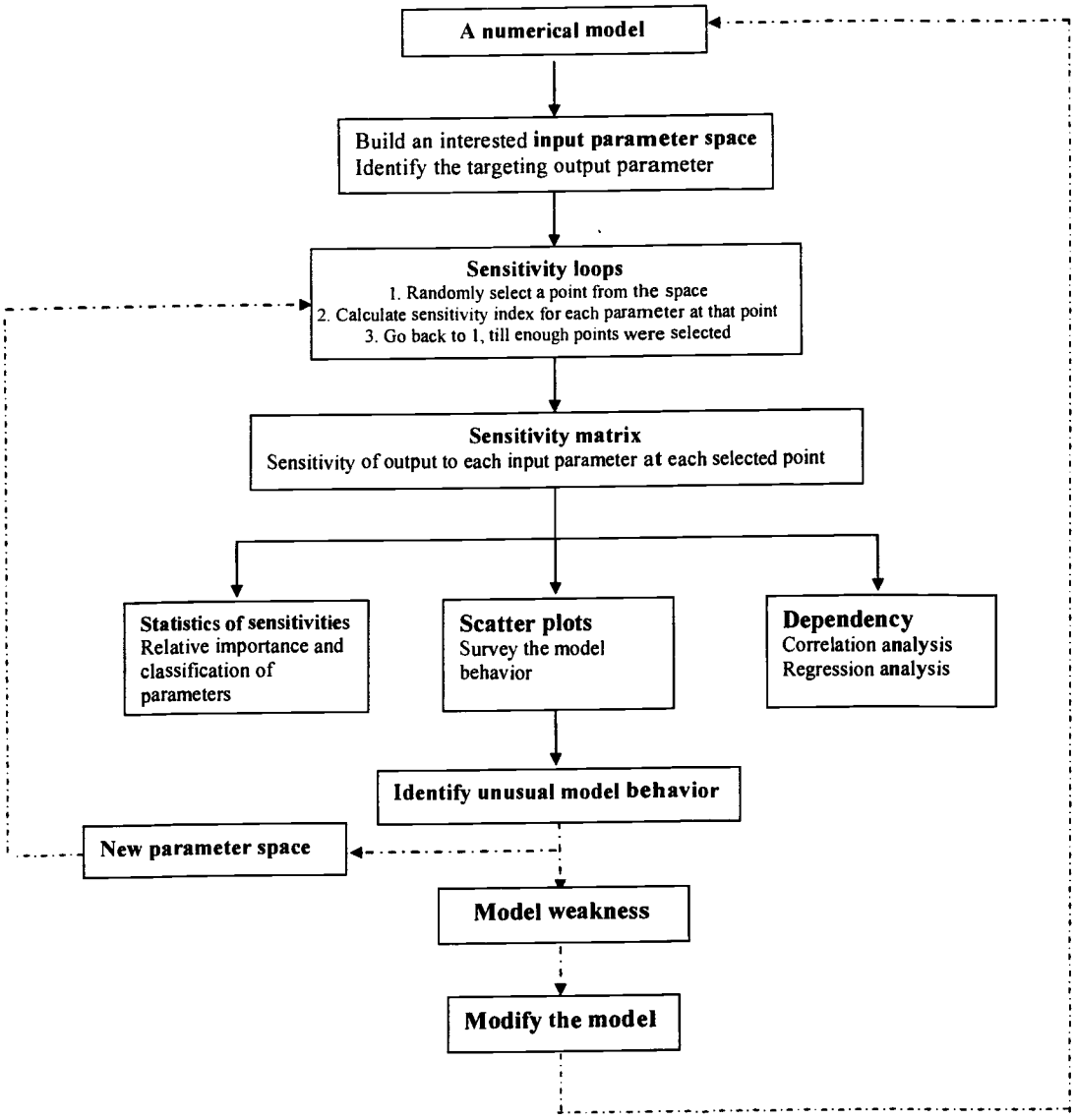

Figure 1. A flow chart of the sensitivity analysis conducted in this paper.

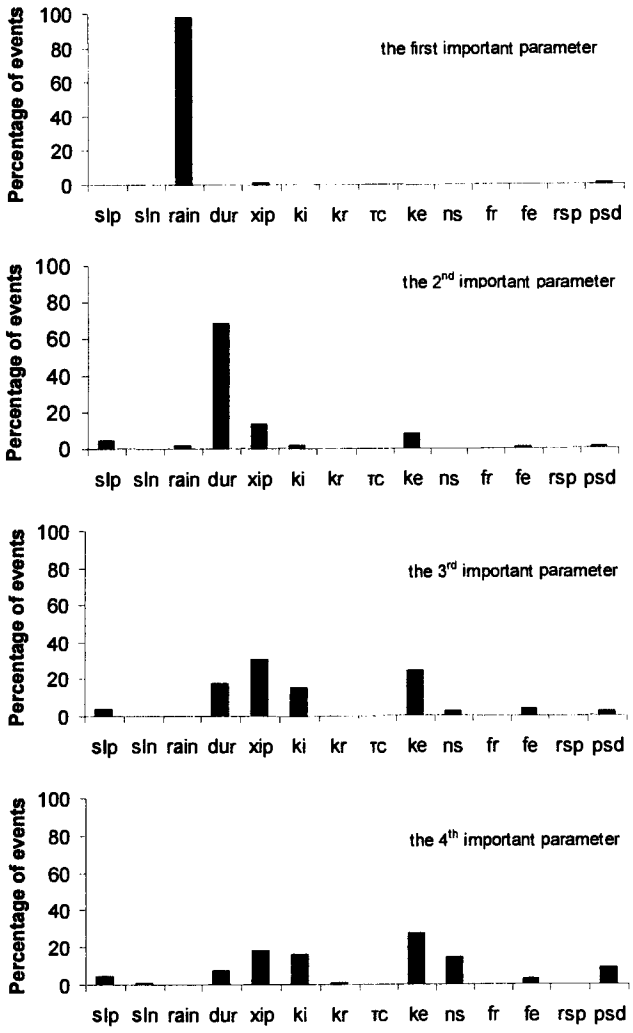

Figure 2. The distribution of the four top-ranked input factors based on the count of events. The first graph shows that *rain* was the most sensitive factor for 97.99% of events, with *psd*, *dur*, *xip*, *slp*, τ_c, and *ke* the most sensitive factors for the remaining 2.01% of the events.

Table 1. Parameters and parameter ranges used in this study.

Parameter	Upper Bound	Lower Bound	Unit	Description
slp	3	30	%	Slope
sln	10	100	m	Slope length
rain	20	120	mm	Rainfall volume
dur	0.5	2	hr	Rainfall duration
xip	1	20	–	Rainfall intensity variable
ki	1000	2000000	kg*s/m^4	Interrill erodibility
kr	0.00001	0.004	s/m	Rill erodibility
τ_c	0.0001	7	N/m^2	Critical shear stress
ke	0.8	40	mm/hr	Effective hydraulic conductivity
ns	0.00025	0.7	m	Matric potential
fr	4.07	200	–	Friction factor for runoff
fe	1.11	100	–	Friction factor for erosion
rsp	0.8	5	m	Inter space
psd	7	–1	–	Particle size distribution

events. For 98.0 percent of the total 3180 events, the total rainfall depth, *rain*, was the most important factor, but *psd*, *dur*, *xip*, *slp*, τ_c, and *ke* also showed up as the top-ranked factors, and these variables accounted for the remaining 2.0 percent of the events. Storm duration, *dur*, was the second most sensitive factor for 68.5 percent of the total events; *slp*, *rain*, *xip*, *ki*, *kr*, *ke*, *fe*, and *psd* accounted for the rest of 31.5 percent events. The third and the fourth ranked important factors were more widely distributed among the input variables (Figure 2). The results show that for a complex model in which the input parameters interact with each other, the sensitivity for input factors may vary greatly from point to point in the parameter space.

Figure 3 gives the distribution of each S_i based on absolute values. The parameters are listed by the ranking of their mean sensitivities, the "overall" effect: *rain*, *dur*, *xip*, *ke*, *ns*, *ki*, *psd*, *slp*, *sln*, *fe*, *fr*, τ_c, *kr*, and *rsp*.

Tiscareno-Lopez et al. (1994) conducted a sensitivity analysis on a similar soil erosion model, WEPP, on the USDA-ARS Walnut Gulch Experimental Watershed located near Tombstone, Arizona. The results from their study indicated that rainfall amount was the most sensitive factor on that watershed, followed by *ke*. From our results, *rain* was the first important factor for 98.0 percent of all the events, followed by either *slp*, *psd*, *ki*, τ_c, or *ke*, depending on the combination of input values. From Figures 2 and 3, one can see that RHEM is a complex model, whereby the localized sensitivities vary greatly from site to site.

Scatter Plots to Identify Characteristics of Model Behavior

In this section we generate the scatter plots of the sensitivity index S_i at each point over the values of the i^{th} parameter at this point to show how this type of scatter plot can be used to help modelers survey the model response and identify nonlinear relationships, thresholds, and potential model problems.

Figure 4 is a plot of S_{psd} over the corresponding *psd* values. The parameter *psd* is important because it is the only factor that accounts for particle size distribution in this study. Figure 4 is a surprising plot because it reveals an unexpected and undesirable model response around the *psd* value of –3.2. The same sensitivity procedures focused on a narrow region of *psd* (–3.0, –3.4) were processed again and this "closer" look confirmed the inconsistent model behavior. For example, for sediment with a *psd* of –3.31, a 5 percent increase in *psd* could induce 70 percent increase in *soil loss*, which was much more sensitive than those simulations with *psd* outside this region. This is not a reasonable model response for this variable.

Dependencies of Sensitivity Indices on Input Parameter Values

We use regression and correlation analysis in this paper to understand the dependence of the sensitivity for a factor on the input parameter values (Table 2). The coefficient of determination, R^2, of the regression describes the percentage of

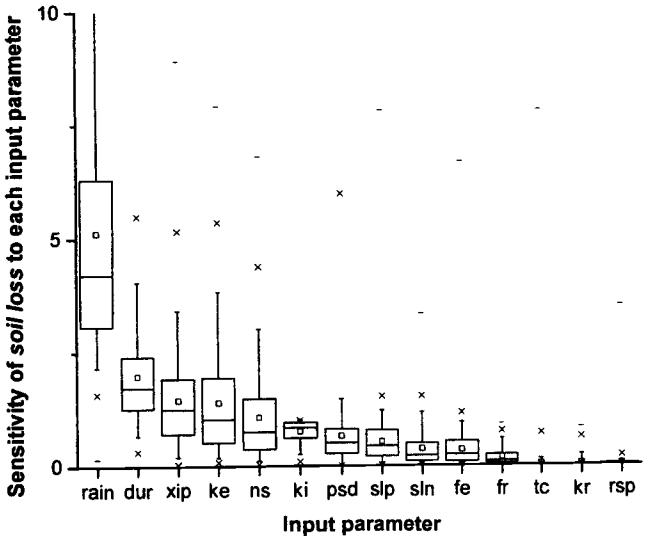

Figure 3. Statistics of absolute sensitivities for each input parameter. The sensitivity on the Y axis only shows values less than 10. The parameters are listed on the X axis by ranking of their mean sensitivities, represented by the smallest boxes. Each S_i is represented as a separate box chart. The box is determined by the 25th and 75th percentiles. The whiskers are determined by the 5th and 95th percentiles. The dash marks are determined by the minimum and maximum values. Descriptions of all input parameters refer to Table 1.

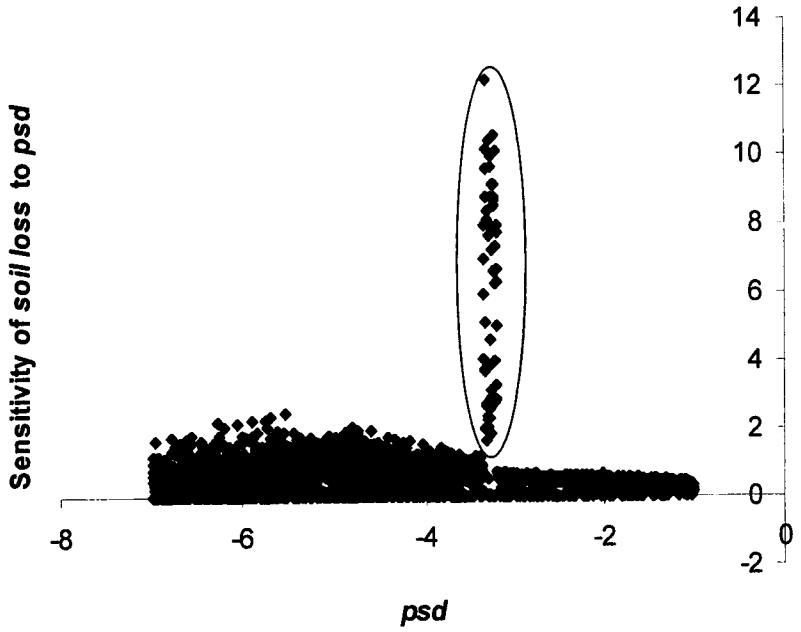

Figure 4. Scatter plot of sensitivity of soil loss to *psd* (S_{psd}) vs. *psd* values. It reveals the incorrect model response when *psd* is close to –3.2.

Table 2. Dependencies of sensitivity indices on the input parameter values.

S_{fr}	S_{sln}	S_{ke}	S_{kl}	S_{rain}	S_{ns}	S_{xip}	S_{fe}	S_{slp}	S_{dur}	S_{kr}	S_{psd}	S_{tc}	S_{rsp}
R^2 of the regression of S_i on the values of the 14 input factors													
0.518	0.511	0.475	0.444	0.432	0.399	0.389	0.376	0.374	0.223	0.220	0.116	0.068	0.024
Correlations coefficient of S_i to each input factors													
kr -0.370	*fr -0.346*	*ke -0.438*	*fe 0.251*	*dur -0.177*	*ns -0.362*	*dur 0.154*	*fr -0.214*	*sln 0.278*	*xip 0.234*	*fe -0.087*	*ki -0.409*	*kr -0.010*	*kr 0.065*
ki 0.325	*sln -0.307*	*rain 0.335*	*ki 0.206*	*slp -0.134*	*rain 0.249*	*fr -0.133*	*sln -0.187*	*fr 0.259*	*fe -0.100*	*ki -0.083*	*fe -0.370*	*ki 0.096*	*rsp -0.044*
fe 0.265	*slp 0.247*	*xip 0.324*	*kr -0.193*	*fr 0.134*	*ke -0.193*	*sln -0.123*	*slp 0.148*	*ki -0.219*	*ki -0.093*	*slp 0.079*	*slp 0.352*	*rsp 0.060*	*sln 0.035*
psd 0.224	*ki -0.109*	*dur -0.282*	*slp -0.171*	*sln 0.125*	*xip 0.180*	*xip 0.108*	*xip -0.063*	*fe -0.185*	*sln 0.06*	τ_c *-0.049*	*psd -0.087*	*fe-0.059*	*fr 0.031*
sln -0.217	*xip -0.102*	*ns -0.241*	*psd 0.165*	*ns -0.103*	*dur -0.135*	*ke 0.100*	*fe -0.056*	*psd-0.153*	*slp 0.06*	*kr 0.046*	*sln -0.072*	*slp -0.051*	τ_c *-0.027*
slp -0.172	*fe -0.094*	*fr -0.198*	*sln -0.16*	*ke -0.099*	*fr -0.125*	*ns 0.089*	*ki -0.045*	*kr 0.145*	*fr 0.05*	*rsp 0.03*	*fr -0.071*	*dur -0.045*	*rain -0.026*
τ_c *0.166*	*rain 0.086*	*sln -0.190*	τ_c *0.158*	*rain 0.096*	*sln -0.110*	*rain -0.072*	*rsp 0.038*	*rain -0.120*	*kr 0.039*	*sln 0.015*	*rain 0.036*	*xip 0.029*	*ke 0.024*
xip 0.162	*kr 0.068*	*slp 0.084*	*rain 0.101*	*xip 0.094*	*slp 0.057*	*slp 0.050*	*rain 0.036*	τ_c *-0.089*	*rain -0.036*	*dur -0.015*	*rsp -0.034*	*psd 0.025*	*ki -0.022*
rain 0.145	*ke -0.068*	τ_c *0.025*	*rsp -0.098*	*ki 0.088*	*rsp 0.021*	*ki 0.019*	τ_c *-0.030*	*ke 0.041*	τ_c *-0.033*	*psd 0.013*	*ns -0.031*	*rain 0.024*	*ns 0.021*
dur -0.127	*ns -0.066*	*psd 0.024*	*fr -0.095*	*fe 0.081*	τ_c *-0.015*	*fe 0.015*	*psd 0.024*	*xip -0.041*	*ns 0.032*	*ke -0.01*	*ke -0.027*	*ke -0.020*	*fe -0.015*
fr -0.122	*dur 0.043*	*rsp -0.018*	*xip 0.089*	*psd -0.020*	*kr 0.006*	*psd 0.012*	*ke -0.023*	*ns 0.035*	*rsp 0.029*	*ns -0.01*	*xip -0.006*	τ_c *- 0.016*	*psd -0.010*
ke -0.060	*rsp -0.039*	*kr -0.017*	*dur -0.061*	τ_c *-0.014*	*psd 0.006*	τ_c *0.002*	*dur 0.014*	*dur 0.033*	*psd -0.025*	*rain -0.008*	*kr -0.003*	*ns -0.014*	*dur 0.005*
ns -0.051	*psd 0.034*	*fe 0.012*	*ke -0.041*	*kr 0.006*	*ki 0.003*	*kr -0.002*	*ns -0.014*	*rsp 0.019*	*ke 0.011*	*xip 0.004*	*dur 0.003*	*sln -0.012*	*slp -0.005*
rsp -0.037	τ_c *-0.021*	*ki -0.001*	*ns -0.040*	*rsp 0.003*	*fe -0.003*	*rsp 0.001*	*kr -0.002*	*slp 0.009*	*dur -0.010*	*fr -0.003*	τ_c *-0.002*	*fr 0.002*	*xip 0.004*

the variance of the sensitivity index that can be explained by the magnitudes of the input parameters. The correlation coefficients of S_i and values of each input parameter reveal the dependence of S_i on each input factor. For example, it can be seen from Table 2 that approximately 50 percent of the variance of S_{fr}, S_{slnv} and S_{ke} could be explained by the magnitudes of the entire input parameter set. The correlation matrix in Table 2 helps to further decompose this dependency. As one can see, S_{fr} is dependent on the factor *kr* and *ki*; thus, the sensitivity of the friction factor of runoff, *fr*, is related to magnitude of the erosion coeffcients.

The coefficients in Table 2 reveal many insights on the relationships between the parameters. For example, S_{ns} and S_{ke} are dependent on the value of *rain*, *dur*, and *xip*. This relationship reflects the fact that the runoff generation in RHEM is controlled by both the rainfall regime (associated with rainfall parameters *rain*, *dur*, and *xip*) and the infiltration regime (associated with hydrologic factors *ke* and *ns*).

Table 2 also shows that there is negative correlation between S_{ke} and *ke*, which indicates that the response of *soil loss* to *ke* is dependent on the magnitude of *ke* itself. The negative correlation coefficient indicates that the higher the *ke*, the more sensitive the *ke*. This relationship makes sense because the high *ke* is often associated with the small amount of runoff and *soil loss*, and the sensitivity of *soil loss* to input factors increases as the *soil loss* value decreases.

CONCLUSION

A sensitivity analysis based on the concept of local sensitivity and Latin hypercube sampling was conducted using the soil erosion component in the model RHEM as a case study. The local sensitivity indices of *soil loss* to 14 input parameters of RHEM at 10,000 points from the full parameter space were obtained and used to build a sensitivity matrix. The sensitivity matrix was analyzed in several ways to draw useful insights on model response and interactions between model parameters: (1) the results highlighted the importance of local sensitivity, which varies from site to site for a complex model such as RHEM. (2) The method was also used to decompose the independency of model response on input parameter values. (3) The method effctively detected model errors.

The method of this paper can be used as an element of the iterative modeling process whereby model response can be surveyed and problems identified and corrected in order to construct a robust model.

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MODELING SPATIAL AND TEMPORAL DISTRIBUTION OF PRECIPITATION IN AN ARIZONA PONDEROSA PINE FOREST ECOSYSTEM

Assefa Desta and Aregai Tecle[1]

Precipitation is governed by physical laws and complex atmospheric processes. Atmospheric processes that generate precipitation systems are complex and spatially and temporally varying, making accurate prediction of precipitation practically difficult. Therefore, precipitation is often evaluated statistically as a random process, in which its future temporal distribution is studied based on its historical distribution pattern (Viessman et al. 2003; Rupp 1995). We developed a stochastic, event-based precipitation model that takes advantage of GIS technology for both cold- and warm-season precipitation events in the ponderosa pine forested watersheds in north-central Arizona. To realistically generate synthetic precipitation data, such a model must consider both the temporal and spatial characteristics of precipitation events in the study area.

The temporal component of the model uses a stochastic process to describe the distribution of precipitation characteristics such as inter-arrival time between events, and the depth and duration of individual storms. The procedure uses appropriate theoretical probability distribution functions and a random number generator to describe and simulate the various precipitation characteristics. The frequency distribution of the inter-arrival time between events is modeled using a univariate Weibull probability distribution function. Depth and duration are modeled using a joint bivariate distribution function to account for their dependency on each other. Using the selected theoretical distribution functions, random numbers are generated for each precipitation characteristic to simulate synthetic time series of precipitation events.

The types of models used depend on the characteristics of the precipitation patterns in the cold and warm seasons in north-central Arizona. Cold-season precipitation events are typically the result of frontal storms coming from the northwest or southwest (Sellers et al. 1985). Storms from the southwest are enhanced by orographic lifting as they rise up the steep side of the Mogollon Rim (Beschta 1976). Warm-season precipitation events are generally monsoonal, convective storms that tend to be highly localized and intensive but short lived, lasting from several minutes to a few hours (Fogel and Duckstein 1969; Fogel et al. 1971). Cold-season precipitation, however, can last more than one day and individual storms may be related to each other by large-scale weather systems. An independent model is used to describe the warm-season precipitation events, whereas cold-season precipitation events are described using a dependent model with additional parameters to adequately describe their characteristics (Duckstein et al. 1975). A test of precipitation models shows that they parallel the cold- and warm-season precipitation patterns in the study area reasonably well; there is reasonable correlation between the simulated and measured relative frequency distributions over the 20 years studied (1962–1982).

We used spatial analysis to define areal distribution of precipitation event depth and duration, as well as the form of precipitation—rain or snow—over the watershed. The event depth and duration at any point on the watershed is described as a function of the point's location in terms of its elevation, aspect, latitude, and longitude, as well as a function of the storm depth and duration simulated at the outlet of the watershed. GIS technology is used with the above functions to generate rasterized images of event depth and duration.

STUDY AREA

We used the largest of the former Beaver Creek experimental watersheds (the Bar M) as a case study to develop the precipitation model. These experimental watersheds are located within the Coconino National Forest in north-central Arizona (Figure 1). The project was established by the Forest Service in 1956 to study the effect of vegetation manipulation on various watershed resources and forest amenities. The outlet of the 6678-hectare Bar

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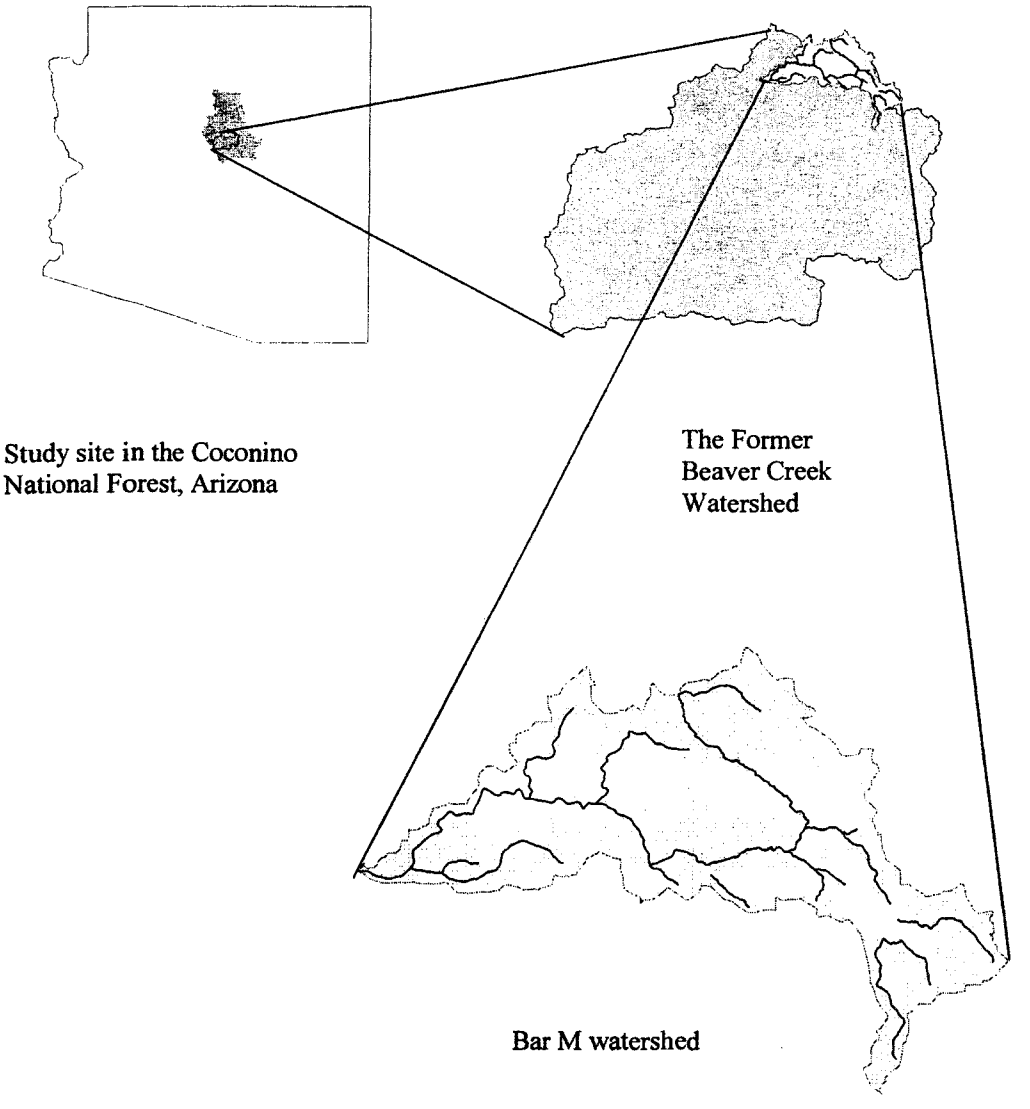

Figure 1. Location of the Bar M watershed in the former Beaver Creek experimental watershed.

M watershed lies at 111° 36' 19" W longitude and 34° 51' 40" N latitude, at 1930 m above sea level; the highest point rises to 2351 m. The watershed is generally inclined southwesterly and has an average slope of 12 degrees. Eighty percent of the Bar M watershed is covered by ponderosa pine (*Pinus ponderosa*), and Gambel oak (*Quercus gambelii*) and aspen (*Populus tremuloides*) cover about 12 and 3 percent of the watershed respectively.

The two major precipitation seasons in the north-central part of Arizona occur in winter and summer. The cold season, which stretches from October 1 to April 30, is mostly characterized by low temperatures and frontal storms (Baker 1982; Rupp 1995). Summer season precipitation events, on the other hand, come mostly in the form of convective precipitation storms during July, August, and September (Baker and Brown 1974).

Winter precipitation in the ponderosa pine type part of the Beaver Creek watershed area averages 431 mm; 60 percent of it comes as snow (Baker 1982). Summer precipitation averages about 216 mm, which is about 33 percent of the annual precipitation (Baker 1982). The highest (18° C) and the lowest (9° C) recorded average monthly summer temperatures occur in July and May, respectively (Campbell and Ryan 1982).

We used precipitation and other climatological data collected between 1962 and 1982 from a network of precipitation gauges in the former Beaver

Creek experimental watersheds. We also used data from the existing multiple-instrumented, state-of-the-art weather and stream gauging facilities at the outlet of the Bar M watershed.

Between 1962 and 1982, approximately 89 precipitation gauges were scattered throughout the area (Figure 2), however all were not operational during the entire 20 years. Some were recording gauges equipped with 24-hour charts, some consisted of standard gauges that were checked weekly, and a few were storage gauges checked at least twice a year. We used only the precipitation data collected from the recording gauges to model the precipitation events.

TEMPORAL ANALYSIS OF PATTERNS

Cold-Season Precipitation

The cold-season precipitation model used in this study follows the one used by Rupp (1995), which is a modified version of the model used by Duckstein et al. (1975). Our model simulates precipitation intensity—the most important variable in determining the amount of surface runoff and water yield.

The first modification to the model involved redefining an "event," which is uninterrupted rainfall or snowfall of any duration, lasting from several minutes to many hours. If it stops raining

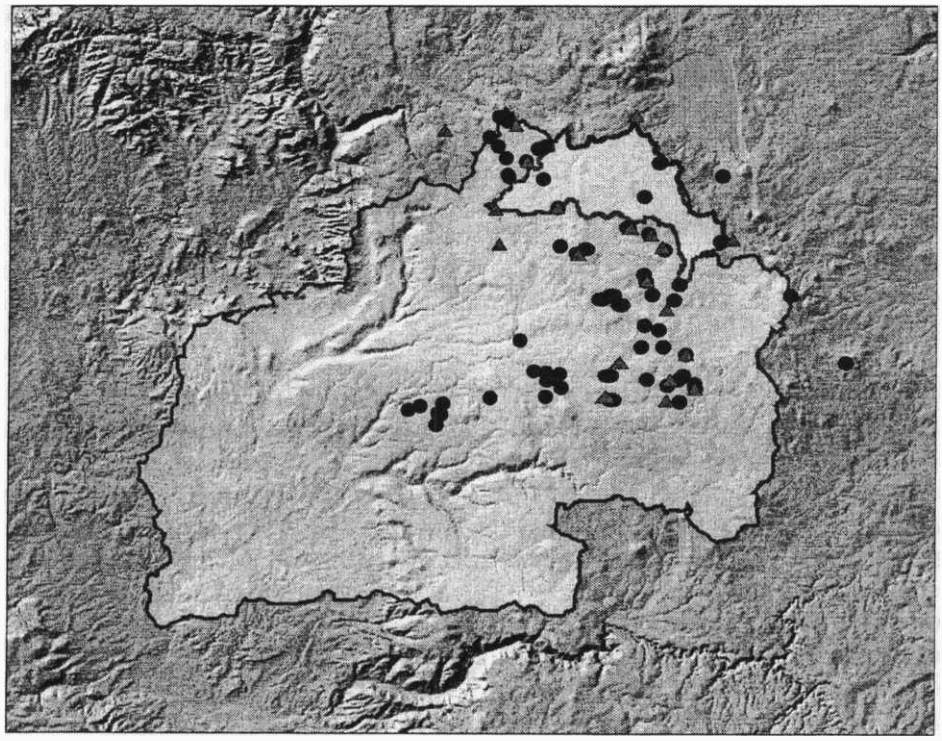

Figure 2. The Bar M watershed and the precipitation gauge network in the former Beaver Creek experimental pilot project.

and then starts again after 5 minutes, the rainfall during the second period is considered a separate event. The second modification was to remove the variable "group." The definition of storm sequence remains the same except for one difference. Duckstein et al. (1975) defined storm sequence as two successive storm events separated by 3 consecutive days of dry weather; their time resolution was 1 day. However, our model recognizes time periods of as little as 5 minutes. For the interval time between storm events, Duckstein et al. (1975) used 2 days for inter-arrival times of 1.5–2.5 days, 3 days for times of 2.5–3.5 days, and so on. For our study the minimum time between consecutive storm sequences was 3.5 days.

The new model, modified from Duckstein et al. (1975) and used in Rupp (1995), is described in terms of the following five variables: time between sequences (days), number of events per sequence, time between events (hrs), precipitation amount per event (mm), and duration of events (hrs). Figures 3 and 4 illustrate the relationships of these variables to each other.

Warm-Season Precipitation

Because consecutive rain events of the convective thunderstorm type are relatively independent from each other, we used an independent event-based model to simulate their temporal distribution (Tecle et al. 1988). We modified the model developed by Bogardi et al. (1988), which dealt with total rainfall depths and durations occurring on consecutive rainy days but did not address the intensity of individual storms. Hence, our modification was needed to allow for the simulation of individual storm event intensities.

The most important change to the model was to redefine an "event," which, as in the cold-season precipitation model, describes uninterrupted rainfall of any duration. The second modification was to remove number of events per season, because our study attempts to describe the general pattern of individual warm-season precipitation events instead of the pattern of storms in a season. The new warm-season precipitation model, which is similar to Bogardi et al. (1988), is described using three variables: precipitation amount per event (mm), duration of events (hrs), and time between events (hrs).

Various theoretical distribution functions have been used in past studies to describe the probability distribution of precipitation characteristics (Eagleson 1972; Duckstein et al. 1973, 1975; Hanes et al. 1977; Rupp 1995). We used SAS statistical software to analyze the observed frequency distribution of the precipitation characteristics while fitting various known theoretical probability distribution functions and identifying the best-fitted model using four goodness-of-fit tests (SAS Institute 2004). Four theoretical probability distribution functions—lognormal, gamma, Weibull, and exponential—were fitted to the frequency distribution of the observed data. Kolmogorov-Smirinov, Cramer–Von Mises, Anderson-Darling, and chi-square tests were used for the goodness-of-fit test to determine appropriate models for the data distributions.

The method of moments is one way of fitting these models to the observed data. The method requires estimating the parameters of the various distribution functions (Barndorff-Nielsen et al. 1996). Some distributions require multiple parameters while others use only one parameter. Parameters of the theoretical distribution functions are estimated from the mean and variance of the observed precipitation characteristics data. Three of the precipitation model variables (time between sequences, number of events per sequence, and time between events) can be described using a univariate probability distribution function (described above). The modeling of depth and duration, however, is more complex because these two variables are not independent of each other. Therefore, a different method was needed, suitable for simulating two dependent random variables. We used a bivariate model, known as ECD, to describe and simulate the dependent variables of depth and duration. The procedure involves explicitly describing the conditional probability distribution of depth, given duration of the event.

SPATIAL ANALYSIS OF EVENTS

We used GIS to describe the spatial distributions of the cold- and warm-season precipitation event characteristics. The various landscape characteristics used for this purpose were gauge elevation, geographic location in terms of Universal Transverse Mercator (UTM), and aspect. Gauge elevation was relevant because many previous studies in the region had already shown that precipitation increases with elevation (Beschta 1976; Campbell and Ryan 1982). Similarly, the UTM coordinates of the gauges were examined to represent the general trend of the Beaver Creek watersheds rising northeastward. Finally, the aspects of the gauge location were analyzed to see if differences in precipitation exist between windward and leeward sites.

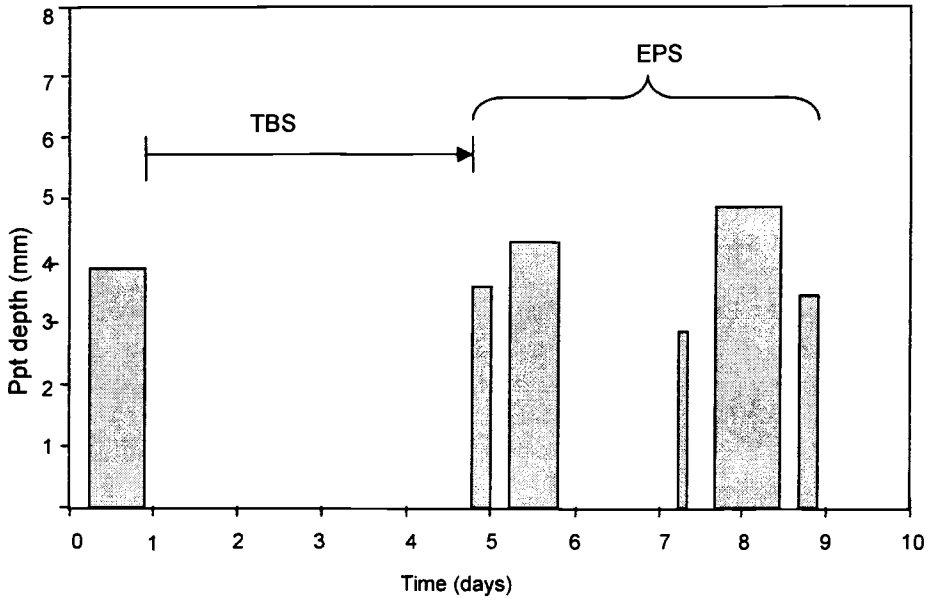

Figure 3. Cold-season model variables for storm sequences.

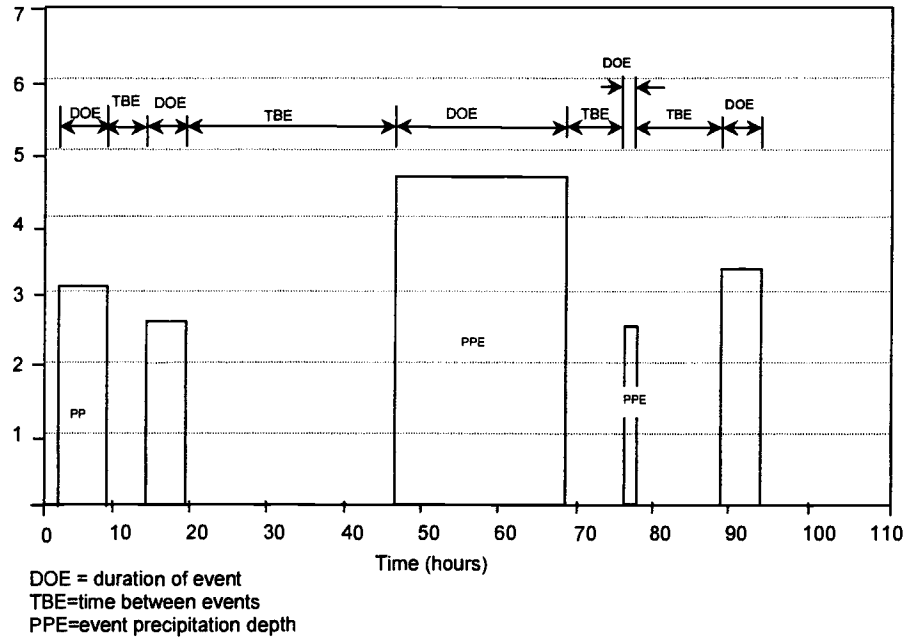

Figure 4. Cold-season and warm-season precipitation model variables for storm events.

The relationships between precipitation depth and the four landscape variables are described in the form of regression equations. After the prediction equations for precipitation depth were determined, we used GIS technology along with the equations to map the spatial distribution of event depth.

Temporal Distribution

Of the four models fitted (lognormal, gamma, Weibull, and exponential) to the time between events data, the Weibull distribution function seems to represent the data better than the others (Figure 5). The distribution of the number of events per sequence was also best described using the Weibull distribution function, whereas gamma distribution seems to fit time between sequences data better. In the case of the joint distributions of depth and duration, the gamma distribution performed best in describing their marginal distribution functions. However, the model failed all the tests at the 5 percent level. We applied the same procedures to each of the precipitation characteristics to determine the best-fit models. The types of models used to describe each variable and the significance levels using the four goodness-of-fit tests are shown in Table 1.

To check the performance of the cold-season precipitation model, we compared the synthetic precipitation data generated by the model with the relative frequency of seasonal total precipitation data actually measured in each cold season during the 20 years of study. The relative frequency histograms of the total measured and simulated data, shown in Figures 6 and 7 respectively, show some differences in the mean and standard deviations of the two data types. The mean and the standard deviation of the seasonal total observed data are 423 and 81.1 mm, whereas those for the simulated data are 482 and 90.2 mm respectively. However, the magnitudes of the most often occurring seasonal total precipitation data for the measured and simulated data are quite similar. The mode of the measured seasonal total is 450 mm, whereas the mode of the simulated seasonal total is 500 mm (see Figures 6 and 7).

We also compared the 20-year seasonal totals of simulated precipitation with those of the observed data to check the performance of the warm-season precipitation model. As shown in the relative frequency histograms of Figures 8 and 9, the differences between the measured and simulated data are small. The mean and standard deviation for the observed seasonal totals are 203 and 58.8

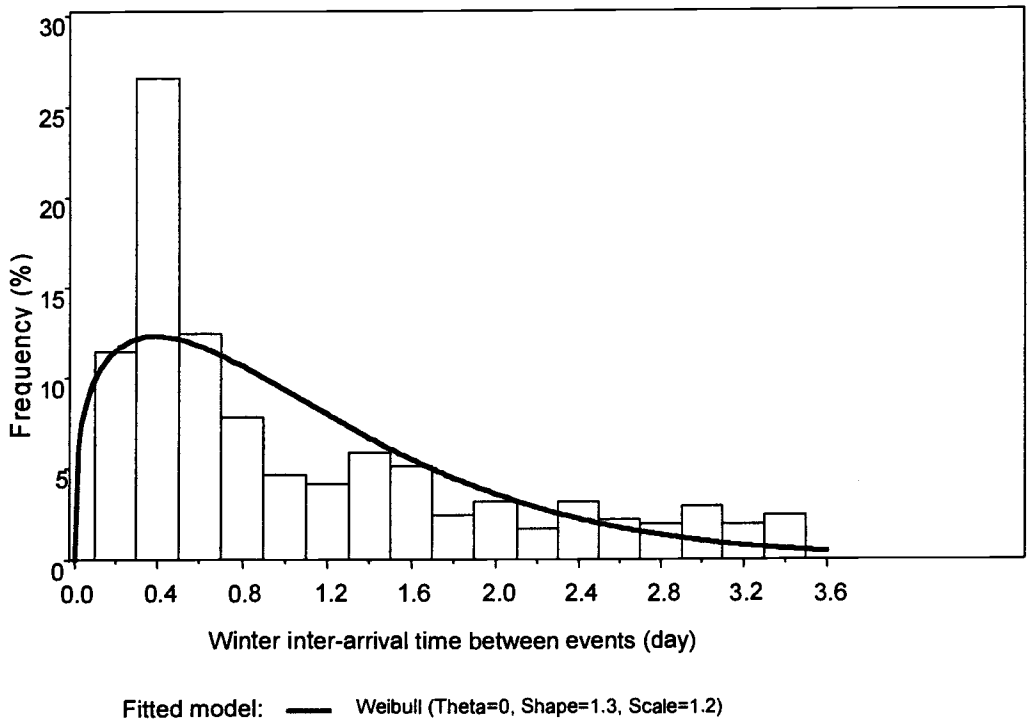

Figure 5. Frequency distribution of inter-arrival time between cold-season events fitted with Weibull probability distribution function (p value = 0.01).

Table 1. The p values for the best-fitted models of cold- and warm-season precipitation events.

Season	Variables	Best-fitted Probability Distribution Functions	Kolmo-gorov-Smirnov	Cramer–Von Mises	Anderson-Darling	Chi-Square	Signi-ficance Level
Cold season	Time between sequence	Gamma	0.5	0.5	0.5	0.184	5%
	No. events per sequence	Weibull	–	0.01	0.01	0.001	5%
	Time between events	Weibull	–	0.01	0.01	0.001	5%
	Duration of events	Gamma	–	–	–	0.035	5%
	Depth of events	Gamma	–	–	–	0.04	5%
Warm season	Time between events	Weibull	–	0.01	0.01	0.001	5%
	Duration of events	Gamma	–	–	–	0.035	5%
	Depth of events	Gamma	–	–	–	0.04	5%

mm, whereas those for the simulated data are 215 and 72.7 mm. The most commonly occurring seasonal precipitation totals in both cases are between 200 and 250 mm. The slight differences between the two data types may be due to data inadequacy and imperfect model fitness. In general, the warm-season precipitation simulation model seems to perform better than the cold-season model.

Spatial Distribution

The spatial variability of the precipitation in the Bar M watershed was analyzed from a subset of the network of precipitation gauges in the Beaver Creek watershed. The selected subset consists of gauges that were operational during the same time period and located nearby to and within the Bar M watershed. Gauges located at elevations much lower than those of the Bar M watershed and in other forest types were excluded. An additional restriction necessary for evaluating storm duration was the use of recording gauges only. Twenty of 89 gauges could fulfill the above criteria for at least a 6-year period. The depths of all the individual storm events were summed separately over the 6-year period to obtain a 6-year total amount of precipitation for each gauge.

A stepwise forward ranking approach was used to select the best predictor from among the four variables and to develop the best-fit regression equation for the change in precipitation depth with space. The best-fit regression equation for the cold-season precipitation depth was expressed in terms of UTM-Y, with little or no contribution from any one of the other three variables (UTM-X, elevation, and aspect; see equation 1). The relationship between UTM-Y and precipitation depth is nonlinear and is expressed using the following third-degree polynomial equation. Based on this equation Figure 10 was constructed to represent the spatial distribution of a particular cold-season precipitation event. As expected, the precipitation event depth increases with an increase in elevation across the entire watershed.

$$P = 2 \times 10^{-13}\,(\text{UTM-Y})^3 - 2 \times 10^{-6}\,(\text{UTM-Y})^2 + 7.827\,(\text{UTM-Y}) - 1 \times 10^{7} \quad [1]$$

$$r^2 = 0.748$$

The spatial distribution of precipitation during the warm season is expressed in terms of the multiple variables UTM-X, UTM-Y, and elevation, as shown in equation 2. The r^2 value for this regression equation is 0.45.

$$P = 1.04 \times 10^{-7}\,(\text{UTM-X}) - 4 \times 10^{-6}\,(\text{UTM-Y}) + 3.77 \times 10^{-4}\,(\text{ELEV}) + 16.88 \quad [2]$$

$$r^2 = 0.45$$

Figure 11 represents the spatial distribution of the warm-season precipitation event depth calculated using equation 2. According to the figure, the amount of summer precipitation ranges from 9.6 to 10.8 mm, with the largest amount occurring on the highest elevation parts of the watershed.

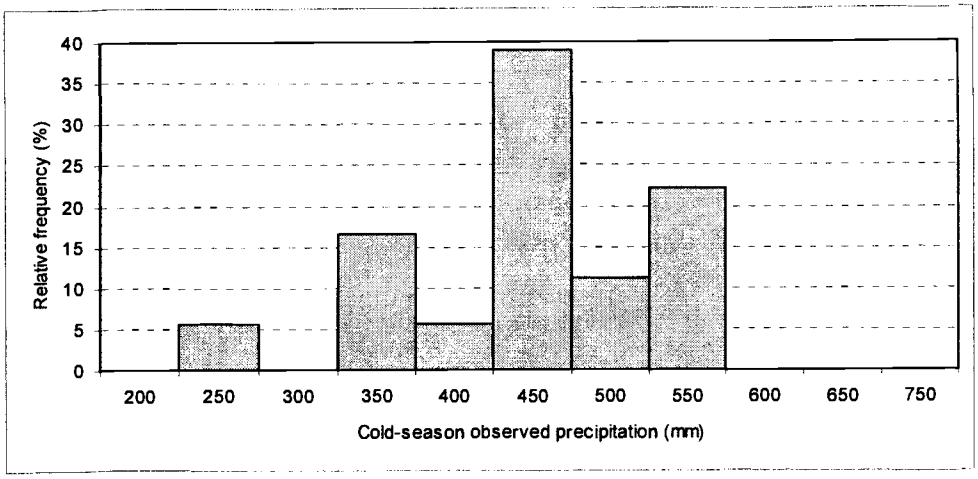

Figure 6. Relative frequency of measured cold-season precipitation total amounts (n = 20 years).

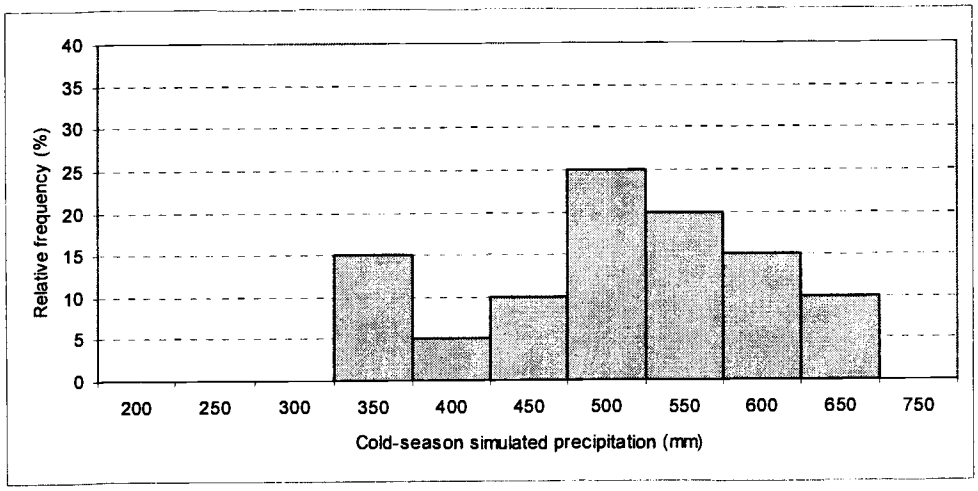

Figure 7. Relative frequency of simulated cold-season precipitation total amounts (n = 20 years).

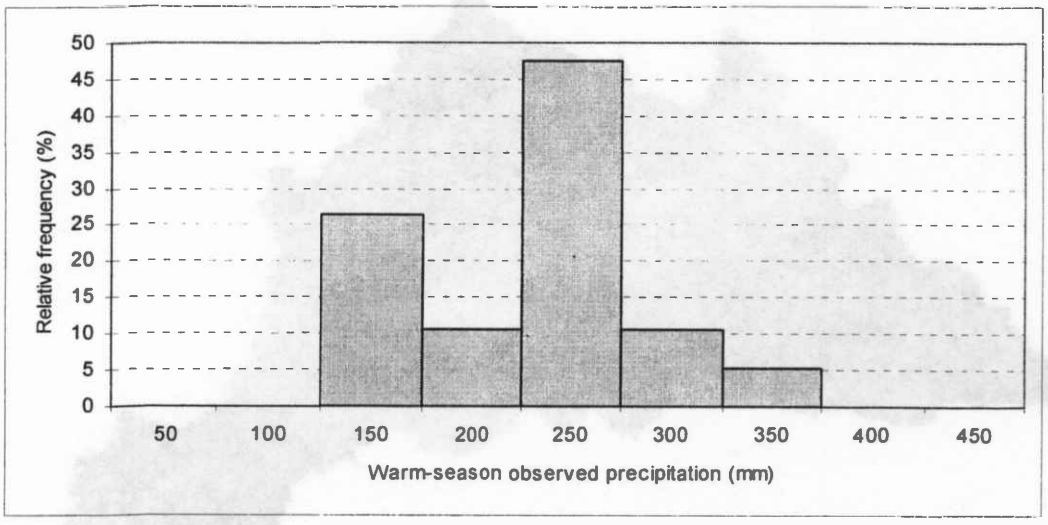

Figure 8. Relative frequency of measured warm-season precipitation total amounts (n = 20 years).

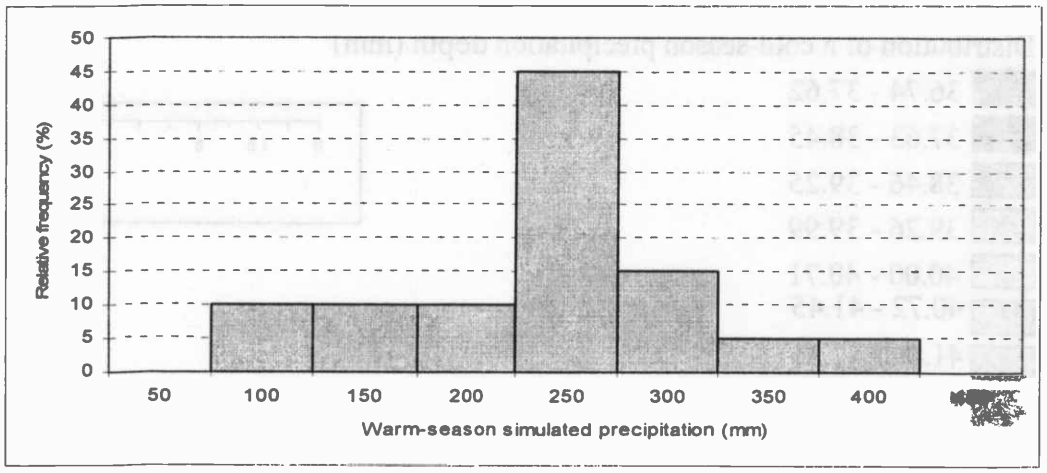

Figure 9. Relative frequency of simulated warm-season precipitation total amounts (n = 20 years).

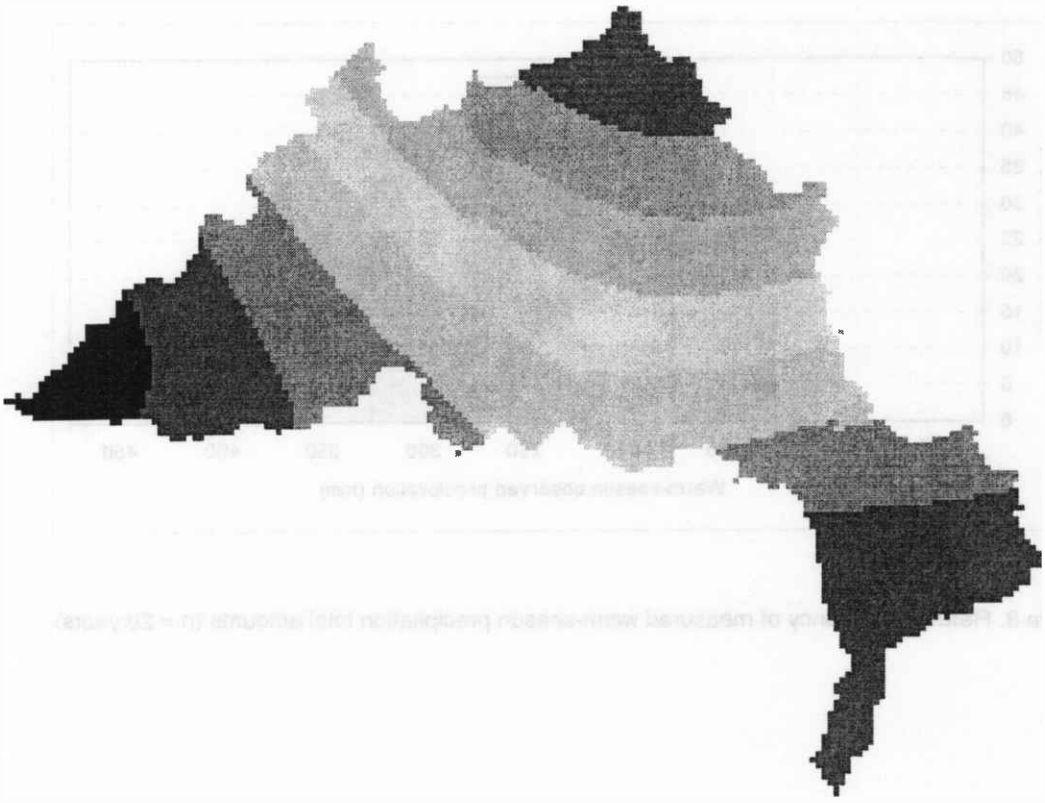

Figure 10. The spatial distribution of a simulated cold-season precipitation event depth.

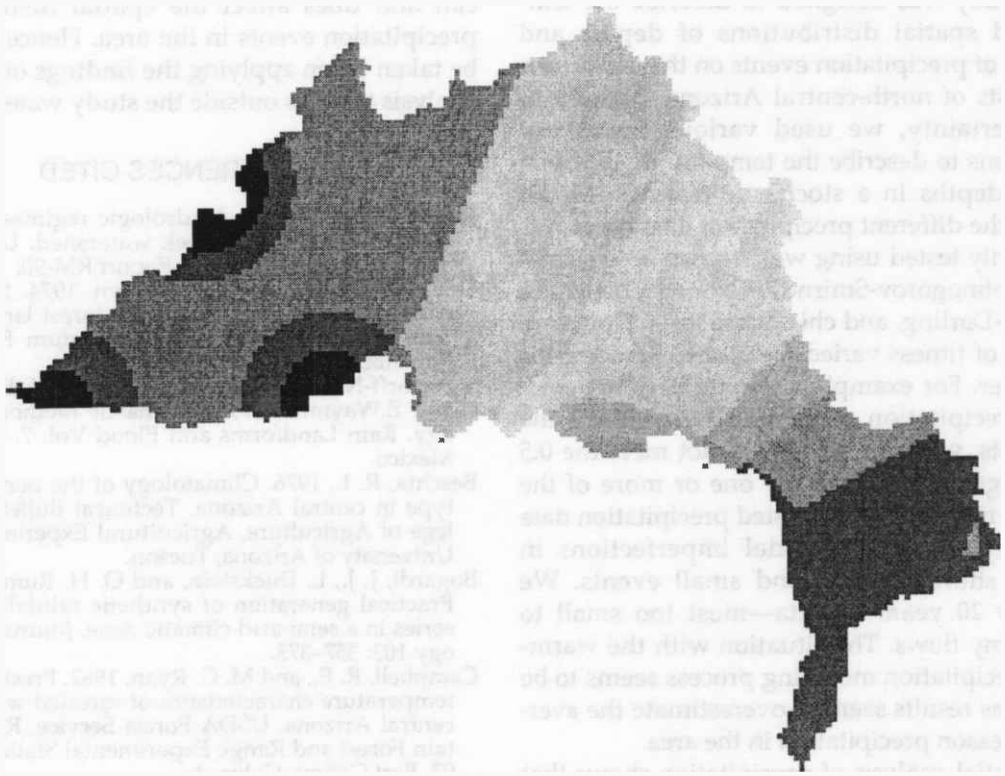

Figure 11. The spatial distribution of a simulated warm-season precipitation storm depth.

SUMMARY AND CONCLUDING REMARKS

This study was designed to describe the temporal and spatial distributions of depths and durations of precipitation events on the ponderosa pine forests of north-central Arizona. Because of data uncertainty, we used various theoretical distributions to describe the temporal distribution of event depths in a stochastic manner. Model fitness to the different precipitation data types was satisfactorily tested using well-known approaches such as Kolmogorov-Smirnov, Cramer–Von Mises, Anderson-Darling, and chi-square tests. However, the levels of fitness varied from one characteristic to the other. For example, the time between cold-season precipitation sequences satisfied all the fitness tests, whereas others did not meet the 0.5 percent significance level for one or more of the tests. This may be due to limited precipitation data availability and some model imperfections in handling short-duration and small events. We used only 20 years of data—most too small to produce any flows. The situation with the warm-season precipitation modeling process seems to be different, as results seem to overestimate the average total season precipitation in the area.

The spatial analysis of precipitation shows that variations in depth and duration of both cold- and warm-season precipitation events are partially explained by the locational characteristics of latitude, longitude, elevation, and aspect of points in the watershed. However, it should be noted that the effects of the individual variables on the spatial distribution of precipitation are different from each other in a season and between seasons. The regression equation for the spatial distribution of cold-season precipitation events is described by latitude (in UTM coordinates) alone, with an r^2 value of 0.65. For the warm season, a multivariate equation consisting of elevation, latitude, and longitude jointly described the spatial distribution of the precipitation depth, with an r^2 value of 0.45. The small r^2 values in both the cold- and warm-season precipitation amounts indicate that significant portions of the spatial variabilities of precipitation depth and duration are left unexplained. Perhaps analysis of individual storms may provide better information on the spatial distribution of precipitation events across the watershed.

There are many factors that may influence the spatial variability of precipitation event depth and duration. For example, the factors controlling the areal distribution of precipitation on watersheds along the Mogollon Rim may be different from those on the Bar M watershed, because the Mogollon Rim is a dominant landscape feature that can and does affect the spatial distribution of precipitation events in the area. Hence, care must be taken when applying the findings of the spatial analysis to areas outside the study watershed.

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AN OVERVIEW OF MULTICRITERION DECISION MAKING IN A SPATIO-TEMPORAL FRAMEWORK

Boris Poff and Aregai Tecle[1]

In 1982 Zeleny wrote that constantly improving computer technology, general scientific progress, and conceptual advancements in integrated decision making were causing a shift in Multicriterion Decision Making (MCDM) from simpler to more complex and less certain decision situations. A review of the relevant literature indicates that the field, though well developed, is still young and its potential has not yet been fully realized. According to Triantaphyllou (2000), MCDM has been one of the fastest growing problem-solving methods over the past two decades. Hence, more than 20 years after Zeleny's prediction, MCDM's potential has not been fully reached, despite the large body of research on the topic.

An essential requirement to solving a problem is complete understanding. A review of the literature helps provide a good understanding of the different components, their interactions in time and space, and how they can be managed in a multiobjective framework. MCDM has its origin in the field of Operations Research (Zeleny 1982), which in turn was started by the military during the Second World War to optimize submarine warfare in the Atlantic Ocean (Morse 1986). Since then, MCDM has been developing into a discipline with its own concepts, approaches, and methods to aid decision makers (DMs) to identify, describe, evaluate, and sometimes sort, rank, and select or reject alternatives, based on evaluation processes that involve several criteria (Colson and De Bruyn 1989; Tecle and Duckstein 1993).

MCDM MODELS

MCDM basically is a technique that describes the performance levels of alternatives in achieving desired management goals. Such description is made by constructing a matrix of criteria versus alternatives. The technique can be divided into two broad classes (Zimmermann 1996; Phoa and Minowa 2005): (1) multi-attribute decision making, which evaluates a finite feasible set of alternatives and selects the best one based on the scores of a set of attributes, and (2) multiobjective decision making (MODM), which selects the best alternative on the basis of its performance with a set of conflicting objectives. Both processes can be used by a single DM or a group of DMs (Phoa and Minowa 2005).

One of the reasons MCDM techniques have not been fully exploited is that managers are still unfamiliar or feel uncomfortable with its tools and methods (Pomerol and Bara-Romero 2000). In business most corporations are preoccupied with single objective (or project) maximization, whereas in ecosystem management DMs are unfamiliar with or lack expertise on the MCDM approach. The few applications of MCDM techniques so far have primarily been in determining optimal timber harvesting methods (Duerr et al. 1979; Garcia 1990). MCDM techniques have primarily assumed homogeneity within a study area and have been basically aspatial (e.g. Poff 2002; Phoa and Minowa 2005), but many MCDM problems in reality vary across space and time (Tkach and Simonovic 1997; Malczewski 1999a).

Even though the integration of MCDM into Geographic Information Systems (GIS) received considerable attention among urban planners (Carver 1991; Malczewski 1996) and in land allocation problems (Jansen and Rietveld 1990; Eastman et al. 1995; Yeh and Li 1998), relatively few studies have employed MCDM with GIS techniques in forest management planning (Phoa and Minowa 2005). In the past few years, GIS has been used to find solutions to natural resource management and planning problems, such as the Patuxent Landscape Model (PLM 1995; Costanza et al. 2002; Voinov et al. 2003), the Everglades Landscape Model (ELM 1997), and the Land Use

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Evolution and Impact Assessment Model (LEAM 1999). This has opened the door for GIS-based multicriteria decision making (Ratsiatou and Stefanakis 2001), leading to the development of spatial decision support systems that incorporate forest planning models into a GIS format (Næsset 1997).

Malczewski (1999b) has suggested that visualization of spatial MCDM analysis outcomes is critical, leading to attempts to combine MCDM tools with GIS. This has led to several prototypes in the past decade (Jansen and Rietveld 1990; Carver 1991; Faber et al. 1995; Jankowski 1995; Lotov et al. 1997; Tkach and Simonovic 1997; Wu 1998; Jiang and Eastman 2000).

There are three basic ways of integrating MCDM into GIS software. The first one involves incorporating MCDM tools into the GIS software (Jiang and Eastman 2000), the second one embeds GIS techniques and tools within the MCDM software (Fisher et al. 1996), and the third integrates both at the operating system level (Jankowski et al. 1997). According to Morris and Jankowski (2000), the main problem with MCDM-GIS integration is that the approach used to assign weights to the criteria is either somewhat arbitrary or assumes that the criteria are strictly Boolean.

One MCDM technique that has been successfully applied in a GIS framework is called Compromise Programming (Rogowski and Engman 1996; Tkach and Simonovic 1997; Bukenya 2000; Simonovic 2002; Thinh and Hedel 2004). Compromise programming selects the solution from a non-dominated set, on the basis of its closest distance from a generally infeasible ideal point. A non-dominated solution to an MODM problem is one that cannot produce any improvement in any one of the objectives without making at least one other objective worse. However, none of the examples mentioned above involve dynamic models and they focus primarily on either cleaning up remotely sensed data or determining land suitability for various natural resource management problems. That is because this area of modeling involves models that are being used to optimize some set of goals or objectives, in terms of planning, design, policy, and management. Planning and management processes are commonly regarded as so complex that it is thought to be not possible to build a spatial model optimized in a fashion that meets the diversity and complexity of the political aspirations of decision makers (Batty 2005).

Some dynamic decision support tools that have been applied on landscape scales include the previously mentioned Patuxent Landscape Model (Costanza et al. 2002; Voinov et al. 2003), the Everglades Landscape Model, and the Land Use Evolution and Impact Assessment Model. These models have allowed decision makers, stakeholders, and concerned citizens to visualize and test impacts of management actions on urban, environmental, social, and economic systems (Maxwell and Voinov 2005). However, none of these models use the classical MCDM/ MODM techniques as defined above.

The closest true spatial-temporal MODM model found in the literature is still conceptual. According to Maidment et al. (2005), three basic questions have to be addressed when setting up a spatial-temporal model: What is the spatial domain of the model and how will that domain be subdivided into analysis units? What is the time horizon for the model and into what intervals will this horizon be subdivided for modeling purposes? What variables will the model determine? These considerations can be illustrated in a data cube as shown in Figure 1.

According to Costanza et al. (2002), although advances in computer technology have made complex simulation models computationally feasible, the difficulty of obtaining a model output that is satisfactory increases sharply with its complexity. They also suggest multiobjective calibration of spatially explicit models, because in many cases only a combination of different objective functions can express the calibration criteria correctly.

SUMMARY

Even though the discipline of MODM/MCDM was developed more than half a century ago, it has not yet reached its full potential. As the boundaries of computing power and technology expand, so do the possibilities of what we can do with MODM/ MCDM. Already advances in computer technology have made complex simulation models feasible, but the difficulty of obtaining satisfactory model output increases sharply with its complexity and in many cases only a combination of different objective functions can express the calibration criteria correctly. Further, applying this discipline in a spatio-temporal scale seems to be a rather new concept, according to what the authors have found in the existing scientific literature. Hence, the future still seems to be wide open and we would like to argue that even though MODM/MCDM

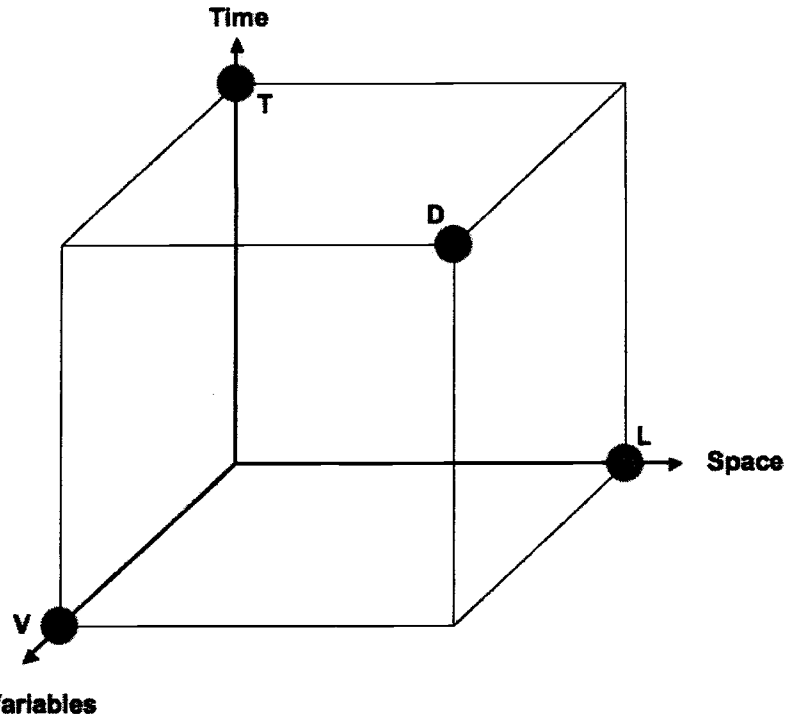

Figure 1. Data for a variable measured at a particular point in space and time. A data value D is a function of what feature it describes, what time it represents, and what variable it is: D(L,T,V) (from Maidment 2002). This conceptual data cube is the basis for the tabular times series model used in the Arc Hydro data model.

may not be in its infancy anymore and has learned how to walk, it still has to learn how to run. This is especially true in management of natural resources such as forests and watersheds. More research and application of spatial-temporal MODM/MCDM in these fields will be necessary to further its practical value.

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A SPATIAL AND TEMPORAL MULTIOBJECTIVE FOREST MANAGEMENT ANALYSIS IN EJIDOS OF DURANGO, MEXICO

Gustavo Perez-Verdin and Aregai Tecle[1]

Mexico hosts a unique land tenure system where the majority of its forest ecosystems belong to communities—*ejidos*—in which all forest resources are collectively owned. Ejidos, a product of a legal process called *dotacion* (endowment), were created to foster economically viable, self-sufficient communities, generally through providing land for cultivation (Barton Brady and Merino 2004). The livelihood of many ejidos, especially in northern Mexico, depends on forest management. However, though they are rich in natural resources, they face many problems associated with poor socio-economic development, inaccessibility, and subsistence (Barton Brady and Merino 2004).

The capacity of forests to produce multiple goods and services in ejido communities has been overlooked in favor of developing alternatives that maximize timber production for economic profit alone. This approach is suboptimal; it leads to ecosystem degradation and fails to address the wishes and aspirations of all stakeholders. Maximization of timber profits still takes precedence in the majority of ejidos and some private forest lands, but the forest law indicates that all landowners must consider other uses and environmental services for the sustainable use of forest resources (SEMARNAT 2003). In spite of such official and practical recognition of the need for multiobjective management of forest systems, there are only a few signs that indicate development and use of technology that embraces multiobjective forest management and the dynamics of forests to evaluate the most preferred mix of resource outputs. Current ejido management plans do address the complex issue of managing forests for multiple objectives, but fail to put them into practice.

The objectives of this paper are threefold: (1) to provide and demonstrate a practical framework to formulate and solve an ejido forest ecosystem management problem in a multiobjective framework that includes identification of most interested parties, forest management objectives, and relevant decision variables; (2) to evaluate stand conditions in a temporal and spatial framework; and (3) to determine target forest structures as references for the multiobjective forest management. The procedure is applied to a real Mexican forest with 10 management objectives representing the most important economic, social, and environmental services currently considered as key strategic elements in the Mexican forest law. The objectives are expressed in terms of three continuous decision variables.

MULTIOBJECTIVE FOREST MANAGEMENT APPROACH

The forest system in one ejido, Los Altares, is used as a case study to formulate and solve a multiobjective forest management problem. This ejido, which is located in northern Durango, features a mix of coniferous temperate forest (*Pinus arizonica, P. durangensis, P. teocote*) and deciduous vegetation types (*Quercus* spp., *Populus tremuloides;* Figure 1). The ejido owns 17,800 ha of forest land of which 93 percent is pine-oak forests. The products/goods are equally distributed among 108 ejidatarios. The ejido's forests have been managed for more than 40 years under uneven- and even-aged management schemes, which included selection, thinning, and seed trees. The annual allowable cut has been decreasing from 16,000 m^3 per year in 1985 to its current level of 6000 m^3 per year. Part of this decline is because of the use of new, more refined forest inventory methods and restructuring of forest stands that include more small-diameter trees, and other natural and human disturbances (UAF Santiago Papasquiaro 2005).

Management Objectives

An objective is the desired direction of change of a state by a decision maker (Duckstein and Tecle 2002). In this study, we used 10 objectives that

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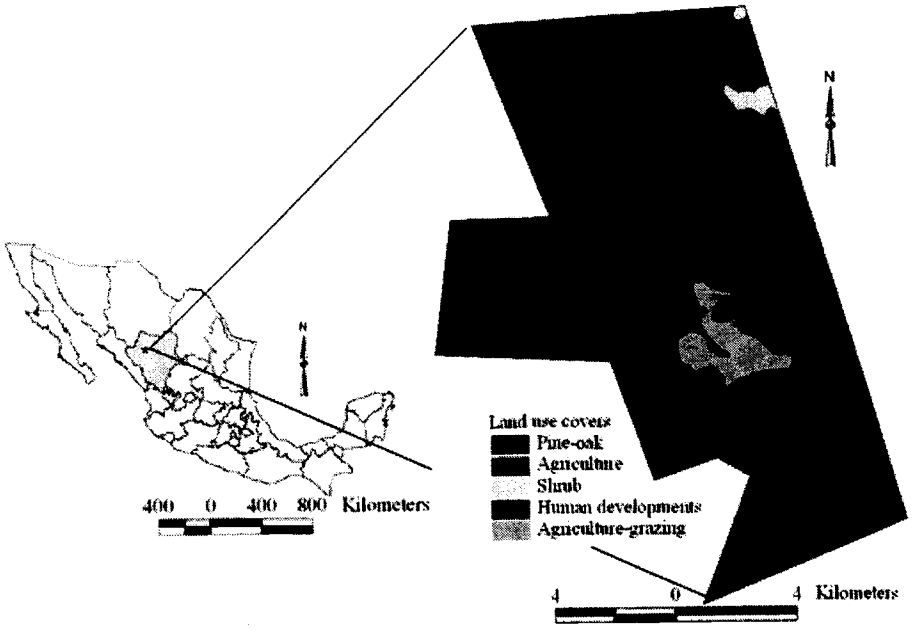

Figure 1. Location of the Ejido Los Altares in Durango, Mexico.

represent the wishes and aspirations of ejiditarios and other interested parties. The 10 objectives are biological richness, carbon sequestration and oxygen provision, fire hazard, non-timber uses (such as mushrooms and resins harvesting), forest/soil productivity, recreation, scenic beauty, soil retention, water supply (quality and quantity), and economic benefits of timber. The identification and uses of these objectives were based upon government information that describes the basis for institutional initiatives in natural resources management, the forest law and other regulations, stakeholders' wishes, and previous works involving ejido multiobjective forest management (Perez-Verdin and Tecle 2002). Four different types of stakeholders were used to generate the relative weights for the 10 management objectives. The four groups of stakeholders—landowners, forest managers, government, and non-government organizations—comprised 144 individuals.

The Decision Variables

Decision variables, which represent the numerical characteristics of the objectives, can be continuous or discrete (Duckstein and Tecle 2002). In constructing the objective functions, we used tree basal area (*ba*), number of trees per hectare (*nth*), and quadratic mean diameter (*qmd*) as the varying, continuous measures of forest conditions. We used more than one decision variable to reflect real forest conditions and to consider the diversity of stands stemming from diverse soil conditions (productivity) and vegetation density and volume. In addition, the three variables are key components in the FVS simulations (Dixon 2002). After converting system units from simulation outputs, *ba* is expressed in m^2/ha, *nth* in trees per hectare, and *qmd* in centimeters.

THE INITIAL FOREST CONDITIONS

Nine forest conditions that show different combinations of the decision variables were used in constructing the 10 objective response functions. Field observations and forest inventory data analysis showed that these forest conditions adequately represented the different forest conditions in the study area. Basal area ranged from 12 to 44 m^2/ha, number of trees varied from a minimum of 160 to a maximum of 2400 individual trees per hectare, and the quadratic mean diameter ranged from 11 to 43 cm.

We photographed each condition (C_i) and showed the pictures to a group of expert consultants to obtain their preference ratings and to construct a response function for each objective. The edited pictures also contained dasometric information. We used the information from expert consultation on the nine forest conditions to con-

struct the response functions to each management objective. The expert information was obtained through personal interviews of 29 expert consultants working in the state of Durango. Their education and professional experience in the field of forest management ranged from doctoral to bachelor degrees and from 45 to 14 years, respectively. Participants also analyzed each photo and answered a questionnaire that relates the possibility for achievement of each objective under the different forest conditions. Rates were based on a 10-point scale where 1 means very low or very bad and 10 means very high or excellent (Table 1).

Response Functions

Using the information from expert consultation and the initial forest conditions, we constructed a multivariate response function for each management objective i. Each objective function is expressed in terms of the three decision variables as follows:

$$y_j = f_i\,(ba, nth, qmd)\ \forall_i \qquad [1]$$

where *ba, nth,* and *qmd* are as defined previously. We used the first partial derivative for each multivariate objective response function i to determine the local maxima y_i^* and minima y_i^{**} of the objectives (Baker 2006) using the following expression:

$$y_i^* = \frac{\partial V_i}{\partial ba_i}; \frac{\partial V_i}{\partial nth_i}; \frac{\partial V_i}{\partial qmd_i}, \forall_i. \qquad [2]$$

Equation 2 was repeated to find the local minima y_i^{**}. This approach requires first that each objective function i be optimized separately to determine y_i^* and y_i^{**} and by looking at the signs of the variables, we were able to determine the maximum or minimum values of each objective function. A step-by-step process to determine both y_i^* and y_i^{**} for one management objective is presented later in the results section. We used the Excel Solver package to determine local maxima and minima values for the rest of the management objectives (Baker 2006). After the local maxima and minima were estimated, we used a distance-based MODM technique called Compromise Programming (CP) to determine the set of nondominated solutions.

COMPROMISE PROGRAMMING

Compromise programming seeks management strategies that minimize the distance between the efficient frontier and a reference point outside the objective space (Krcmar et al. 2005). The solutions closest to the ideal are called compromise or nondominated solutions (Goicochea et al. 1982), which means a solution to a multiobjective problem for which there exists no other feasible solution that will cause improvement in any of the objectives without making at least one other objective worse (Tecle et al. 1998). The procedure for evaluation of the set of nondominated points is to measure how close these points are to the ideal solution. The measure of closeness is defined by a family of distance metrics, d_p (Zeleny 1982), and any point in the objective space can be a compromise solution if it minimizes

$$d_p = \left[\sum_{i=1}^{I} \lambda_i^p \left(y_i^* - y_i\right)^p\right]^{1/p},$$

$$\forall_i, \lambda_i > 0, 1 < p < \infty, \text{ and } \sum_{i=1}^{I} \lambda_{i=1} \qquad [3]$$

where p is the distance parameter, y_i^* is the best or maximum value (local maxima) for objective i, y_i is the value of objective i, and I is the number of objectives considered. The parameter λ_i is the relative weight of objective i. Varying the value of p between 1 and infinity allows one to move from minimizing the sum of individual regrets (i.e. having a perfect compensation among the objectives) to minimizing the maximum regret (i.e. having no compensation among the objectives) in the decision-making process (Tecle et al. 1998). To minimize the scale effects in the compromise solutions, a standardized equation in which distance values use relative rather than absolute deviations is proposed (Zeleny 1982; Tecle et al. 1998). The standardized form of equation 3 is expressed as follows:

$$d_p = Min\left[\sum_{i=1}^{I} \lambda_i^p \left(\frac{y_i^* - y_i}{y_i^* - y_i^{**}}\right)^p\right]^{1/p} \qquad [4]$$

where y_i^{**} represents the worst or minimum value (local minima) for objective i. The notion of p represents the emphasis given to the size of individual deviations on the outcome. The three most common p values used in computing compromise solutions are 1, 2, and ∞. A sensitivity analysis is performed to verify the consistency of the nondominated solutions under varying values of p and objective weights λ_i (Goicochea et al. 1982; Zeleny 1982; Krcmar et al. 2005). Having λ_i in equations 3 and 4 represents the decision maker's

Table 1. Standardized weights, means, and standard deviations (in parentheses) for the management objectives and forest conditions derived from expert consultation.

Objective	Weights	Forest Conditions								
		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
Biodiversity richness	0.104	7.8 (1.6)	6.9 (1.1)	6.8 (1.7)	7.1 (1.7)	6.5 (1.1)	5.3 (1.3)	5.7 (1.2)	6.6 (1.5)	6.6 (1.4)
Carbon sequestration	0.100	8.8 (1.3)	8.2 (1.0)	7.7 (1.0)	8.0 (1.3)	6.9 (0.7)	5.9 (1.2)	5.7 (1.2)	7.3 (1.3)	6.9 (1.3)
Fire hazard	0.108	7.4 (1.1)	7.1 (0.9)	7.2 (1.3)	7.2 (0.8)	6.8 (1.4)	5.9 (1.6)	5.9 (1.6)	7.5 (1.3)	7.0 (1.0)
Non-timber products	0.082	6.9 (1.8)	7.0 (1.6)	6.3 (1.4)	7.3 (1.5)	6.6 (1.2)	6.4 (1.3)	6.3 (1.2)	5.8 (1.4)	7.2 (1.7)
Forest productivity	0.106	8.5 (1.2)	8.1 (1.1)	7.3 (1.5)	8.1 (0.8)	7.2 (0.8)	5.7 (1.2)	5.8 (1.4)	6.6 (1.4)	7.0 (1.5)
Recreation	0.093	6.5 (1.9)	7.2 (1.9)	5.6 (1.8)	7.8 (1.6)	6.4 (1.5)	6.2 (1.3)	5.7 (1.5)	5.0 (1.6)	6.9 (1.5)
Scenic beauty	0.094	6.8 (1.5)	7.3 (1.7)	5.9 (1.5)	7.7 (1.2)	6.6 (1.3)	6.2 (1.3)	5.8 (1.6)	4.8 (1.6)	7.0 (1.4)
Soil retention	0.104	8.6 (0.9)	7.9 (0.9)	7.3 (1.3)	7.5 (1.3)	7.1 (1.2)	6.5 (1.3)	6.2 (1.2)	7.9 (1.2)	6.9 (1.6)
Timber economic benefits	0.102	7.9 (1.1)	7.9 (1.8)	6.1 (1.3)	7.8 (1.3)	6.9 (1.1)	5.9 (1.2)	5.7 (1.4)	5.2 (1.3)	7.4 (1.9)
Water supply	0.107	6.6 (1.7)	6.9 (1.4)	6.7 (1.3)	6.9 (1.3)	6.9 (1.0)	7.1 (1.2)	7.5 (1.6)	6.3 (1.3)	7.4 (1.3)

preference structure among the objectives (Goicochea et al. 1982). Thus, a double-weighting scheme to verify the consistency of the nondominated solutions exists. The parameter p reflects the importance of the maximal deviation and the parameter λ_i reflects the importance of the different objectives relative to each other (Goicochea et al. 1982).

SPATIAL AND TEMPORAL ANALYSIS OF THE MODM APPROACH

We used a cluster analysis to group sampled forest conditions according to the decision variables (number of trees per hectare, quadratic mean diameter, and basal area) plus age, and species composition. Any variation due to location of stands with similar forest characteristics should be reflected in the clustering scheme. We identified the clusters using the average within-groups linkage method, measured by the Euclidian distance (Romesburg 1990), which produced 15 groups. Within each cluster we identified the single stand that most represented the average characteristics of the cluster. This stand was then used in the temporal analysis of the problem. Stand information consisted of site index, tree density, slope, elevation, and factor numbers that converted data from 0.1 ha, fixed-sized plots to units per acre. Tree information included type of species, diameter, and height. The results for a stand were generalized to the cluster it represented.

The Forest Vegetation Simulator (FVS), Central Rockies variant, simulated forest growth, regeneration, and mortality of the representative stands that resulted from the spatial clustering. FVS relies on a family of forest growth simulation models derived from individual-tree, distance-independent data that simulate a wide variety of forest types, stand structures, and pure or mixed species stands (Crookston and Dixon 2005). We used the FVS Central Rockies variant in Durango's forests because of the similarities in vegetation types between the U.S. Southwest and the study area, and the flexibility of the simulator. Also the ecosystems in the U.S. Rocky Mountain region and those in northern Mexico share similar characteristics in terms of species composition and growth patterns (Richardson 1998).

We considered the following parameters in the FVS simulation. A planning period of 100 years was divided into 10-year cycles. The planning period of 100 years is the average time a typical tree would need to mature in the study area. Regeneration of the dominant species (i.e., *Pinus arizonica* and *Quercus* spp.) was established at 340 and 140 trees per ha at age 5, respectively. The rotation cycle for uneven-aged stands was determined to be 13 years with a slope (q) of the inverse J-shaped diameter distribution equal to −1.4 (Meyer 1952; UAF Santiago Papasquiaro 2005). Using the FVS tool we simulated various forest scenarios and examined the results for each 10-year time step until an optimal solution—that is, the closest distance to the ideal—was found. This procedure was repeated for each of the 16 clusters.

RESULTS AND DISCUSSION

The expert opinion values on the initial forest conditions with the three decision variables (*ba*, *nth*, and *qmd*) were used to construct the response functions for all management objectives. A test of normality of residuals, using the Shapiro-Wilk test, and other statistical parameters (R^2 and p values) were considered in determining model fitness. We solved the partial derivatives of the different objective functions to find their local maxima y_i^* and minima y_i^{**} values (Baker 2006; see equations 6 through 15 in Table 2). The vector of y_i^* and y_i^{**} values constitutes, respectively, the ideal and the worst points needed to solve the problem using compromise programming (equation 4).

After we constructed the response functions and determined the local maxima and minima values for all objectives, we used equation 4 to determine the set of compromise solutions. This involved finding the closest distance between the efficient frontier and the ideal point for each time step (one 10-year cycle) and cluster. In this case, an iterative process was performed for each time step and cluster by simulating different forest scenarios until stand structures approached the ideal solution as closely as possible. The ideal point corresponds to a vector of the maximum values of the different objective response functions.

Simulation of forest growth using FVS to approach the ideal point was not easy. Some clusters were understocked in terms of basal area, but overstocked with regard to number of trees per hectare. FVS simulations considered various silvicultural treatments, such as thinning from above, thinning from below, individual selection, and seed trees, and leaving different levels of residual density. Outcome simulations were analyzed through the statistical report and the postprocessor stand visualization system, which generates three-dimensional drawings of FVS outputs (Crookston and Dixon 2005). Unfortunately, FVS does not support more than one target goal during simulations, so in some clusters the process was repeated for each decision variable. Tables 3, 4, and 5 show the results of the compromise solutions for each time step and cluster and for each decision variable.

Sensitivity Analysis

A sensitivity analysis was conducted to test the robustness of the algorithm with respect to any changes in p and the weights of the objectives, λ_i. Since the process consisted of examining continuous and multiple decision variables, we used Excel solver to determine the robustness of the model when the values of the parameters p equal 1, 2, and ∞. The results show no changes in the compromise solution for $p = 2$ and ∞ and only a slight change in the value of *nth* for $p = 1$.

The second sensitivity analysis consisted of examining the effects of changing the weights of objectives, λ_i. Different weights representing the preference structures of various landowners and other stakeholders on the objectives were keyed into the compromise programming algorithm. The results showed no significant changes in the CP (compromise programming) solutions with changes in the weights.

To further verify that the solution was not sensitive to changes in the objective weights, we performed two additional tests. The first one involved use of different weights for the objectives, and the second one consisted of assigning equal weights to each management objective when determining the preferred solution. In both cases, target forest structures remained unchanged, that is, there was no model sensitivity to changes in the values of the parameters, λ_i. We believe that the results are not sensitive to changes in p or λ_i values because the difference between the objective response functions and the ideal point is so big that any change in these two parameters does not affect the results.

SUMMARY AND CONCLUSIONS

This study described a practical approach to a dynamic formulation and solution to a multiobjective forest management problem in the Ejido Los Altares, Mexico. Various management objectives, decision variables, and opinions of stakeholders were used to solve the multiobjective forest

Table 2. Objective response functions, statistical fitness of models, and local maxima and minima values.

Objective	Model[1]	Equation	p value	R^2	Residuals Test[2]	Max[3]	Min[3]
Biodiversity richness	$y_1 = 4.01 + 0.05(ba) + 2.6E^{-4}(nth) + 0.029(qmd)$	[5]	0.008	0.84	0.67	8.08	4.99
Carbon sequestration	$y_2 = 3.67 + 0.074(ba) + 0.0004(nth) + 0.044(qmd)$	[6]	0.02	0.78	0.71	9.81	5.15
Fire hazard	$y_3 = 5.64 + 0.004(ba) + 0.0007(nth) + 0.043(qmd) - 14.16(1/ba)$	[7]	0.02	0.85	0.56	5.144	9.034
Non-timber products management	$y_4 = 5.23 + 0.009(ba) - 8.0E^{-5}(nth) + 0.043(qmd)$	[8]	0.002	0.92	0.88	7.47	5.63
Forest productivity	$y_5 = 3.76 + 0.074(ba) + 6.8E^{-5}(nth) + 0.045(qmd)$	[9]	0.009	0.83	0.71	9.12	5.19
Recreation	$y_6 = 3.82 + 0.01(ba) - 5.2E^{-5}(nth) + 0.081(qmd)$	[10]	0.004	0.91	0.87	7.75	4.72
Scenic beauty	$y_7 = 4.41 + 0.02(ba) - 4.15E^{-4}(nth) + 0.06(qmd)$	[11]	0.002	0.90	0.62	7.82	4.33
Soil retention	$y_8 = 5.022 + 0.04(ba) + 4.9E^{-4}(nth) + 0.023(qmd)$	[12]	0.05	0.69	0.75	8.96	5.85
Timber economic benefits	$y_9 = 3.88 + 0.046(ba) - 0.00034(nth) + 0.064(qmd)$	[13]	0.02	0.82	0.97	8.66	4.45
Water supply	$y_{10} = 6.95 - 0.021(ba) - 3.7E^{-4}(nth) + 0.058(qmd) + 0.104(\log nth)$	[14]	0.05	0.79	0.74	9.68	6.59

[1] Models include the following variables: y_i = values of forest conditions; ba = basal area; nth = number of trees per ha; and qmd = quadratic mean diameter.
[2] Based on the Shapiro-Wilk test for normality of residuals.
[3] The maximums and minimums were determined using partial derivatives of the models.

Table 3. Target forest conditions (compromise solution) in basal area (m^2/ha).

	Time step (years)									
Cluster	10	20	30	40	50	60	70	80	90	100
0004	9.9	10.1	10.8	11.2	11.7	11.7	10.1	10.8	11.5	11.7
0238	19.3	17.2	18.1	18.8	19.3	19.3	19.3	19.1	19.1	18.8
0245	5.7	1.8	2.5	3.2	4.1	5.3	6.7	7.6	9.0	9.9
0291	20.2	20.2	21.8	21.4	21.8	22.3	22.3	22.3	22.3	22.5
0537	14.5	17.4	20.4	23.4	25.9	27.3	28.5	29.6	30.5	31.7
0601	17.2	18.1	18.4	18.6	18.8	19.3	19.5	19.5	19.7	19.7
0788	15.4	14.5	13.5	13.1	13.8	14.7	15.4	15.6	15.8	15.8
0958	16.8	18.6	18.8	18.8	19.1	21.1	23.2	24.8	26.6	27.5
1043	18.6	17.0	16.3	17.4	18.4	18.6	18.8	17.4	18.1	18.6
1119	17.2	16.8	15.8	16.5	17.4	18.1	18.4	18.4	18.6	18.6
1122	23.4	23.2	22.7	23.4	23.9	23.9	23.9	24.1	24.1	24.1
1142	5.5	2.1	2.8	3.7	5.1	6.4	7.1	8.5	8.7	9.4
1309	12.9	14.9	17.0	17.2	17.2	17.0	17.0	17.2	17.2	17.2
1411	19.3	18.8	17.7	17.0	17.9	18.8	19.7	20.0	20.0	19.7
1452	6.4	3.4	7.6	12.2	13.3	12.4	12.2	11.9	13.1	13.5

Table 4. Target forest conditions (compromise solution) in number of trees per hectare.

	Time step (years)									
Cluster	10	20	30	40	50	60	70	80	90	100
0004	512	432	356	292	240	618	427	341	274	227
0238	897	665	556	482	430	390	353	319	282	250
0245	519	971	867	613	554	440	403	336	316	282
0291	168	138	642	581	516	457	388	331	287	252
0537	306	301	297	292	287	277	267	257	250	242
0601	635	588	536	492	450	413	381	343	314	277
0788	662	949	1068	717	558	445	361	289	237	193
0958	242	235	222	208	195	190	188	183	180	173
1043	808	1028	670	524	420	343	746	531	440	358
1119	744	1112	783	598	499	430	373	324	287	250
1122	358	776	655	571	507	432	366	309	259	222
1142	418	761	746	731	660	600	445	408	316	274
1309	166	163	161	151	368	343	321	304	287	274
1411	652	993	1156	788	625	509	425	348	292	240
1452	492	848	635	492	803	914	961	502	336	237

Table 5. Target forest conditions (compromise solution) in quadratic mean diameter (cm).

	Time step (years)									
Cluster	10	20	30	40	50	60	70	80	90	100
0004	15.7	17.3	19.6	22.4	24.9	15.5	17.5	20.1	23.1	25.7
0238	16.5	18.0	20.3	22.4	23.9	25.1	26.4	27.7	29.2	31.0
0245	11.7	4.8	5.8	8.1	9.9	12.4	14.5	17.0	19.1	21.3
0291	38.9	42.9	20.8	21.6	23.1	24.9	27.2	29.2	31.5	33.8
0537	24.4	27.2	29.7	32.0	34.0	35.6	36.8	38.1	39.6	40.9
0601	18.5	19.8	20.8	22.1	23.1	24.4	25.7	26.9	28.4	30.0
0788	17.3	14.0	12.7	15.2	17.8	20.6	23.4	26.2	29.2	32.3
0958	29.7	31.8	32.8	34.0	35.3	37.6	39.6	41.7	43.4	45.2
1043	17.0	14.5	17.8	20.6	23.6	26.2	17.8	20.6	22.9	25.7
1119	17.3	14.0	16.0	18.8	21.1	23.1	24.9	26.9	28.7	30.7
1122	29.0	19.6	21.1	22.9	24.6	26.4	29.0	31.5	34.5	37.3
1142	13.0	5.8	6.9	8.1	9.9	11.7	14.2	16.3	18.8	21.1
1309	31.2	34.0	36.8	38.1	24.4	25.1	25.9	26.9	27.7	28.4
1411	19.3	15.5	14.0	16.5	19.1	21.6	24.4	26.9	29.5	32.3
1452	13.0	7.4	12.4	17.8	14.5	13.2	12.7	17.5	22.4	26.9

management problem in a spatial and temporal framework. We used an MODM tool known as compromise programming to determine the preferred solutions (Tecle 1992; Tecle et al. 1998; Srinivasa and Pillai 1999; Krcmar et al. 2005). Tree and stand data were dynamically assessed using the forest vegetation simulator for each 10-year step of the 100-year planning period.

Target forest structures were determined for each of the 15 clusters in which the study area was divided. As noted in the sensitivity analysis, target forest structures were generally above current stand conditions, particularly in terms of basal area and quadratic mean diameter. Many factors might have contributed to the differences between current and target conditions in the study area. For instance, forests have been managed for timber harvesting purposes only in which intensive selection cuttings, oriented to the best individuals, have decreased the stocking and quality of residual trees. Gaps and edges have produced unbalanced or pulsated diameter distributions (Gingrich 1993), which caused some complications in determining the target structures. Another factor is the required human activity to clear the forest areas for other purposes such as agriculture, roads, and grazing. Cattle are also evident throughout the study area, and all these factors together are jeopardizing the forest's capacity to fully regenerate.

The differences between reference conditions and current stand characteristics show that managing the forests for multiple objectives is different from the traditional way of managing forest systems for timber production alone. Traditional forest management for the sole objective of maximizing profit from timber production resulted in unbalanced diameter distributions, low stocking, and bad product quality. We believe that the transition to this new approach will gradually occur as the ejidos, their forest managers, and environmental groups and other institutional agencies recognize the importance of other forest resources. The methodology presented in this study may serve as the initial tool to transit to this new paradigm.

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IMPACTS OF A HIGH-INTENSITY SUMMER RAINSTORM ON TWO SMALL OAK SAVANNA WATERSHEDS IN THE SOUTHWESTERN BORDERLANDS

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Oak (encinal) woodlands and savannas cover more than 31,000 square miles in the southwestern United States and northern Mexico. About 60 percent of the Coronado National Forest supports oak woodlands and savannas. Emory oak (*Quercus emoryi*) is the most common species in many of the ecosystems. The lands are important for recreation, wildlife habitats, livestock production, and tree products and resources. The ecosystem's trees and herbaceous cover protect important watersheds that provide local water for human and animal populations and support important riparian habitats. They often contain channels that transport water originating from higher-elevation forests to the lowlands where it is utilized. However, little is known about the hydrology of these ecosystems (Lopes and Ffolliott 1992; Baker et al. 1995), although there have been recent studies designed to learn more about the components of the hydrologic cycle within these stands. Ffolliott et al. (2003) and Shipek et al. (2004) studied transpiration of harvested and unharvested Emory oak trees and stands and Haworth and McPherson (1991) studied the effects of Emory oak on the distribution and interception of precipitation. Ffolliott (2004) used this information to develop a water balance for oak woodlands in southeastern Arizona. He assumed that if annual precipitation was 18 inches, only 4–10 percent would become streamflow. Most of the precipitation would contribute to the interception and evapotranspiration components of the hydrologic cycle. Differences in runoff can be related to soil type and condition, plant cover characteristics, and range condition (Baker et al. 1995).

Streamflow and sedimentation data are not available for the oak woodlands and savannas of the southwestern United States. Much of the hydrologic research in the region has been conducted in the semiarid grassland vegetation at Walnut Gulch near Tombstone, Arizona, by the USDA Agricultural Research Service (ARS). However, the ARS has recently conducted rainfall simulation studies on burned and unburned oak and grassland sites (Paige et al. 2005). Surface runoff generally is the result of rainfall, especially runoff generated by high-intensity summer convectional storms although sustained winter storms have produced significant runoff events in the region. Snow does occur in the region's mountains, but the importance of snowmelt runoff is localized to lands surrounding the higher-elevation mountain ranges such as the Santa Catalina Mountains and the Pinaleno Mountains (Ffolliott et al. 1996).

In 2000, the Southwestern Borderlands Ecosystem Management Project of the U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station and its cooperators initiated a study in the Peloncillo Mountains to determine the effects of cool season (November–April) or warm season (May–October) prescribed burning on the hydrology, erosion, and sedimentation dynamics of oak savannas in the Southwestern Borderlands. This effort was in response to questions raised during the preparation of the Peloncillo Programmatic Fire Plan by the Coronado National Forest and its partners. Parshall flumes were established on 12 small watersheds and recording precipitation gages were located in a grid throughout the research area.

A secondary objective was to learn more about the basic hydrology of this oak ecosystem. The overall study uses an ecosystem approach and also includes studies of the impacts of seasonal burning on vegetation, fuels, and wildlife (Gottfried et al., in press).

Pre-treatment calibration of the flumes began in 2001. The calibration period continues because the

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prolonged regional drought has limited the number of flow events available to compare runoff peaks among watersheds. However, on August 23, 2005, a high-intensity thunderstorm crossing the watersheds produced high peak flows that overtopped several of the flumes and moved large amounts of side-slope and channel sediments. This paper presents preliminary information about the impacts of the storm on two of the watersheds, one draining to the south and the other draining to the north. The information will increase our knowledge about the hydrology and sediment dynamics of the widespread oak savanna ecosystem.

STUDY AREA

The study area, known as the Cascabel Watersheds, is located on the eastern side of the Peloncillo Mountains and west of the Animas Valley of southwestern New Mexico. It is within the Douglas Ranger District of the Coronado National Forest and adjacent to the Diamond A Ranch. The study area covers approximately 451 acres with individual watersheds ranging from about 59 to 19 acres. The watersheds are located along an east-west ridge with six draining to the south into Whitmire Creek and six draining to the north into Walnut Creek. The watersheds have been divided into four groups of three; one watershed in each group will be burned in the cool season, one will be burned in the warm season, and one will remain unburned as a control. Elevations range from 5594 feet on the west side of the study area to 5380 feet on the east side. Long-term average annual precipitation at the Cascabel Ranch headquarters gage is 23.5 inches, with nearly half occurring during the summer.

The geology and soils for the watershed area have been described in detail by Gottfried et al. (2000), Youberg and Ferguson (2001), and Robertson et al. (2002). The bedrock geology is described as Tertiary rhyolite lava overlain by Oligocene-Miocene conglomerates and sandstone. Rhyolite is more apparent on the three western watersheds. Soils on the watersheds have been classified as Lithic Argiustolls, Lithic Haplustolls, or Lithic Ustorthents (Robertson et al. 2002). Soils generally are less than 3.3 feet deep. Streams on the north side of the central ridge have longer, lower gradient channels than those on the south side. This difference might be related to the geomorphology of the two major creeks that border the study area—specifically, their relative sizes, lithologic changes, and relative location with respect to the central ridge (Youberg and Ferguson 2001). Whitmire Creek to the south is closer to the ridge than Walnut Creek which is to the north of the study area.

Emory oak is the dominant tree species on the watersheds, comprising about 60 percent of the tree composition (Gottfried et al., in press). Arizona white oak (*Q. arizonica*), Toumey oak (*Q. toumeyi*), and alligator juniper (*Juniperus deppeana*) are other important species. The density is about 90 trees per acre. Common grasses include several species of grama (*Bouteloua* spp.), *bullgrass (Muhlenbergia emersleyi*), and common wolfstail (*Lycurus phleoides*). Forbs are a relatively minor component of the understory. Shrubs and half-shrubs, such as beargrass (*Nolina microcarpa*), are scattered on the area.

The current evaluation is based on preliminary runoff and precipitation on two of the western watersheds—Watershed A and Watershed I. These two were selected because of the quality of the record and the relative concentration of precipitation gages. Data from the two areas will not be compared statistically. Watershed A, which drains to the south into Whitmire Canyon, covers 31.5 acres and lies at an average elevation of 5550 feet. The channel is 1378 feet long (Neary and Gottfried 2004) and has a slope of 5.6 percent. Side-slopes, based on map measurements, average about 23 percent. The geology is rhyolite with some boulder-cobble conglomerate on the upper ridges (Youberg and Ferguson 2001). The lower slopes are dominated by Lithic Ustorthents, while the ridges have Lithic Argiustolls soils (Robertson et al. 2002). The textures are a very cobbly sandy loam and a very gravelly sandy loam, respectively. Watershed I, which drains to the north into Walnut Creek, covers 52.4 acres and has an average elevation of 5530 feet. Channel length is 5320 feet and channel slope is 3.8 percent. Side-slopes average 17 percent. The geology is boulder-cobble conglomerate (Youberg and Ferguson 2001) and the dominant soils are Lithic Argiustolls (Robertson et al. 2002).

Channel substrate is an important factor in streamflow, base flow, and the availability of sediments for transportation. Channel characteristics for the two watersheds are shown in Table 1.

METHODS

Runoff and Precipitation

Each of the 12 watersheds contains a 9-inch Parshall flume, with a capacity of 4.03 cubic feet per second (cfs) to measure common low flows,

Table 1. Channel characteristics by percent of channel for Watersheds A and I (Neary and Gottfried 2004).

Characteristic	Watershed A	Watershed I
Rock	6.4	15.9
Fine alluvium	24.7	3.0
Coarse alluvium	62.4	74.0
Vegetation	4.6	6.4
Woody debris	0.7	0.7
Other	1.2	0.0

and a larger 3-foot or 4-foot flume with capacities of either 42.7 or 57.5 cfs, respectively. These values assume that the flume is running at 90 percent of full depth. The flume size was determined from pre-installation calculations based on a 10-year return interval and a 2.8-inch rain event within 24 hours (Gottfried et al. 2000). Watersheds A and I contain 4-foot flumes. The small flumes were converted to Replogle long-throated flumes in 2005 to increase their accuracy to measure low flows. Two weather stations were established, one at the western edge of the area and one on a side-ridge in the middle of the area. These are supplemented by six additional recording dipping bucket precipitation gages located throughout the area. For this analysis we used the Watershed H weather station (H Cascabal) on the ridge between Watersheds A and H, the Watersheds A-B dipping bucket gage between Watersheds A and B, and the Watershed I dipping bucket gage near the Watershed I flumes.

Sediment

Sediment is measured at a sediment dam and basin on each watershed. The dam walls are about 2–3 feet in height and are tied into the channel walls. Every dam wall contains an opening to minimize streamflow retention. Each basin contains 10 surveying lines that are tied to a permanent benchmark. These are measured periodically using a surveyor's level and rod. Volumes and volume differences between periods are calculated using the WinXSPRO program (Hardy et al. 2005) and the average end area method (Dendy et al. 1979). In addition, each watershed has a series of permanent channel cross-sections that are also measured with a level and rod. Surface pebble counts were conducted in all basins in 2006. Side-slope erosion is measured at a series of three-pin groups located on five transects that are orientated perpendicular to the main channels within each watershed. Local bulk density measurements were used to convert measurements of average soil loss to erosion rates in terms of tons per acre. Watersheds A and I each have 12 erosion plots that are measured in the spring and fall.

THE STORM OF AUGUST 23, 2005

The Borderlands region and most of the Southwest are currently in the seventh year of a protracted drought. However, there were significant storms on the Cascabel watersheds in January and at the end of February 2005. Some of these winter storms produced measurable runoff. The watersheds received about 2.88 inches of precipitation between January 2 and 6, producing peak flows of 2.0 and 2.2 cfs on Watershed A and 7.5 and 6.5 cfs on Watershed I. Conditions were then relatively dry until mid-July when monsoon rains began to enter the area. Approximately 1.80 inches of rain occurred in July but these storms did not generate any runoff. August was relatively wet; about 5.58 inches of rain fell between August 3 and 22. Two storms produced daily total accumulations of more than 1 inch. Intermittent runoff was measured from Watersheds A and I starting on August 10 when 1.49 inches were recorded at the H Cascabel weather station.

The storm of August 23 began at 12:00 hours and came from the northwest. Some of the storm's characteristics are indicated in Table 2. Periods of high-intensity rain have been converted to equivalent inches per hour values. Other gages on the study area recorded between 2.81 and 1.36 inches of total precipitation. The two gages at the eastern end of the study area recorded the least precipitation. The storm also started between 9 and 21 minutes later on those areas. Gages at Watersheds I and K on the north-facing side of the area recorded the greatest intensities. This storm was the last big monsoon event of 2005 although two smaller spotty storms crossed the area in early September.

RESULTS AND DISCUSSION

Runoff

Four runoff events were measured on Watersheds A and I in August 2005 prior to the storm of August 23. These occurred on August 10, 11, 14, and 20. Flow from the August 23 storm began at the big flume on Watershed A at 12:16 hours and peaked at 13:00. The peak stage was 2.48 feet and the peak flow was 67.20 cfs. This big flume stage was almost at maximum for a 4-foot Parshall flume. However, the debris cover on the walls at Watershed A indicates that this level of flow was likely. We do not know the character of the recession flow because the big flume orifice was

Table 2. Precipitation characteristics for gages surrounding Watersheds A and I at Cascabel for the storm of August 23, 2005.

Station	Total Precip. (inches)	Starting Time (hour)	Ending Time (hour)	Equivalent Highest Intensity (in/hr)
H Cascabel	2.36	12:00	16:00	1.90
Watershed A-B	2.64	12:01	15:44	2.94
Watershed I	2.99	12:06	15:47	3.31

blocked by fine material at approximately 13:09 hours. The downstream small flume began recording at 12:30 but became inoperative because its throat was blocked by a 9-inch cobble and large amounts of vegetative material.

Watershed I began recording runoff at about 12:05 and peaked at 13:02 at a stage of 2.12 feet on the big flume, which indicates a peak flow of 52.57 cfs. Flow was recorded at the big flume until 17:25 that day, lasting 5 hours and 20 minutes. Runoff was measured at the small flume for another 5 days, until 18:09 on August 28. A 0.08-inch storm on August 26 contributed to the sustained flows. Much of the precipitation from the large storm probably became surface or subsurface runoff and little was held by the soil or channel sediments. The flumes at Watershed I started measuring flow about 5 minutes after the storm started at H Cascabel and at about the same time as the I-dipping bucket started recording. The rapid flow response could have been the result of direct channel interception and rapid flows over the bedrock in the channel; peak flow was measured after an hour of rain.

The Soil Conservation Service's curve number procedure was used during the planning phase to simulate a unit hydrograph for each of the 12 watersheds (USDA Soil Conservation Service 1984). The procedure assumes that some of the precipitation does not contribute to runoff. The method classifies watersheds by hydrologic soil groups based on runoff potential, infiltration rates, and water transmission rates, and by hydrologic condition, based on degree of ground cover. A runoff curve number of 84, out of a maximum of 100, was used in the original calculations for all watersheds. Times of concentrations (Tc) were recalculated for the two watersheds based on measurements made after the flumes were installed. The Tc value is defined as the time it takes for runoff to travel from the hydrologic, most distant point of the watershed to its outlet. The Tc values are 8 minutes for Watershed A and 26 minutes for Watershed I. If we assume that the peak flow includes water from all areas of the watershed, which actually is unknown, the estimates for Watershed A and I are too low. However, the value of Tc on unregulated upland streams can be compromised because of pool filling and the formation and breaching of debris dams upstream. The sediment dam walls may have retarded some of the initial flow although they are designed with an opening to minimize their effect. The influence of the dams decreases as the basins are filled with sediment and hold less water. An even distribution of rainfall cannot be assumed because of the cellular nature of summer thunderstorms.

Runoff response is also influenced by subsurface geology. For example, some of the rhyolite coherent facies in Watershed A are relatively impermeable to surface runoff infiltration (Youberg and Ferguson 2001) and would yield water quickly. New calculations of potential peak discharge values for a 10-year recurrence interval based on a curve number of 84 and the new Tc were 60 cfs for Watershed A and 68 cfs for Watershed I. The observed values were 67 and 53 cfs, respectively. It is possible that closer agreement could have occurred if individual curve numbers had been selected for each watershed.

EROSION AND SEDIMENTATION

The storm moved sufficient sediments from side-slopes and redistributed existing sediments in the channels to fill most of the sediment basins located above the flume installations. The small flumes at Watersheds A, B, and H were made inoperative because of the accumulation of large cobbles and vegetative materials including live trees and tree trunks.

Side-Slope Erosion

The erosion pins on Watersheds A and I were measured in the spring and fall of 2005 (Table 3). The first period reflects conditions after the winter

Table 3. Side-slope erosion on Cascabel Watersheds A and I for the 2005 measurement dates.

	Spring 2005		Fall 2005	
Watershed	tons/acre	cubic feet/acre	tons/acre	cubic feet/acre
Watershed A	9.94 ± 1.25	281.83 ± 35.46	10.80 ± 1.25	306.21 ± 35.46
Watershed I	17.70 ± 2.33	502.19 ± 66.09	4.62 ± 0.95	130.99 ± 26.95

storms and the second after the summer events. The spring 2005 values reflect changes since the fall of 2004. The measurements at Watershed A for the two periods are statistically equivalent. The decrease during the summer relative to winter for Watershed I might be linked to the fact that much of the soil had already been moved before the summer storms began. Although we cannot confirm this fact quantitatively, one indication is that peak flows were larger on Watershed I than on Watershed A during the storms of early January 2005.

Similar watershed data from other areas in the southwestern United States are not available for comparison. Paige et al. (2005) reported sediment yields of between 0.94 and 1.97 tons/acre for two small rainfall simulation plots in unburned oak woodland in the San Rafael Valley in southeastern Arizona. However, these values only reflect one event. Nearing et al. (2005) studied 40 years of erosion on two small watersheds at Walnut Gulch, Arizona. One was covered by grass and the other by brush such as creosote (*Larrea tridentata*) and whitethorn (*Acacia constricta*). The brush-covered watershed yielded 1.9 tons/acre/year but eroded areas within the watershed yielded an average of 2.5 tons/acre/year. The values for the grass watershed were 0 and 1.4 tons/acre/year, respectively.

Sediment Dam Measurements

The basins behind the sediment dams collect channel sediments that are redistributed by stream flow and new sediments that are moved from the side-slopes into the channel system. The lower section of the Watershed A sediment basin, containing six transects, was surveyed, cleared of sediments, and resurveyed in late March 2005, providing a comparison of sedimentation that occurred during the 20 months between August 2003 and March 2005 and the 10 months between April 2005 and January 2006 when the dam was surveyed and cleared again. Approximately 52.2 ft^3 of sediment were collected in the first period, which included the storms of January and February 2005, and 190 ft^3 were collected in the second period, which included the storm of August 23. These accumulations are the equivalent of 1 and 7.2 ft^3/acre/year, respectively. Similar information is not available for Watershed I because cleaning of sediments was not necessary in March 2005.

All 10 transects across both sediment dams were surveyed in January 2006. Approximately 295.3 ft^3 of sediments were measured behind the Watershed A dam. The total collected since 2003, including material removed in March 2005, was 347.4 ft^3. The proportion of the 306.2 ft^3 that eroded from the side-slopes during the summer period (Table 3) and was deposited at the dam site is unknown. Much of the eroded material that entered the channel was probably redistributed there. The amounts for Watershed I from December 2003 through January 2006 were 190.3 ft^3. The totals for the full period of record were equivalent to 4.4 ft^3/acre/year for Watershed A and 1.7 ft^3/acre/year for Watershed I.

There are few sedimentation studies in the region with which to compare the Cascabel results. However, Nichols (2006) reported long-term results from eight large semiarid grassland watersheds at Walnut Gulch, an area that receives between 11.9 and 13.4 inches of annual precipitation. This analysis was based on sediment-yield data that covered from 30 to 47 years of record. The Cascabel sediment yields are smaller than those from Walnut Gulch, where yields ranged from 7.1 to 42.9 ft^3/acre/year of sediment and averaged 20.0 ± 14.3 ft^3/acre/year. These watersheds have primarily alluvial channels with little exposed bedrock.

There also appear to be differences in the size of sediments collected at the flume sites and in the sediment dams (Table 4). Most of the sediments coming from both watersheds were in the sand and gravel categories; however, sands were more common at Watershed A. Some of the finer material collected behind the dam and in the upstream channel (Table 1) consisted of volcanic glass that was weathered from the rhyolite formations. Gravels were more common on Watershed I and could

Table 4. Percent distribution of sediments in Watershed A and I determined by pebble counts.

Class Name	Size (in)	Watershed A	Watershed I
Sand	<0.8	46.3	23.3
Gravels	0.08–2.5	33.3	61.8
Small cobbles	2.5–5.0	6.5	7.5
Large cobbles	5–10	9.9	1.5
Small boulders	10–20	4.0	1.5
Medium boulders	20–40	0	0
Large boulders	40–80	0	0
Very large boulders	80–160	0	4.4

be related to its very gravelly sandy loam soils. It is probable that larger material that was moved by the peak flows was buried under the surface or had been moved through the flumes during the peak flow part of the hydrograph. Some of the soil that eroded from the side-slopes probably remained in the channels after flow had ended. Much of the measured finer material settled out of the streamflow during the recession flow. Suspended sediments were not measured.

More sediment was produced on Watershed A than Watershed I since the sediment basins were originally measured in 2003. It is difficult to draw conclusions for the entire study period but there are several potential reasons for the differences in the period surrounding August 23. The differences in geology and geomorphology appear more important than the differences in aspect. The differences in channel length and slope affect the hydrologic characteristics. The peak flows were higher on Watershed A, providing the energy to move more and larger-sized material that had been collecting in the channel over time or was washed into the channel from the side-slopes. Although the 2005 side-slope erosion data appear similar for the two areas, there were larger losses from Watershed A during the summer period. Channel conditions would have had an impact. There is more channel alluvium in Watershed A (87.1%) than in Watershed I (77%), which provides a potential source of material. Watershed I has more exposed bedrock in the channel that would not contribute to sediment yields in the short term.

SUMMARY

There is little information about the hydrology, erosion, and sedimentation characteristics of the oak savanna ecosystems that cover wide areas in the southwestern United States and northern Mexico. This paper attempts to help alleviate this deficiency by describing the impacts of a high-intensity summer rainstorm in 2005 on two small watersheds that are typical of the area's savannas. Although only a small area was studied, the information could be applicable to similar watersheds throughout the region and could be used, with caution, when planning management activities. Streamflow is intermittent; dry channels are more common than flow events, and most events are less than 1 cfs. However, large streamflow events do occur, especially in the summer monsoon period, and they can move large amounts of sediments. Flows of 67 cfs were measured on August 23 at Watershed A and on several adjacent watersheds that were not included in this analysis. Side-slope erosion and sediment movements and characteristics should provide useful information as well. It appears that watershed geology and geomorphology are the main factors influencing the amounts and types of sediments measured from the two watersheds.

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ECOSYSTEM IMPACTS OF ARTIFICIAL SNOWMAKING AT ARIZONA SNOWBOWL

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Snowmaking is becoming a popular method of increasing snow cover, depth, and level according to the needs of ski areas to fulfill the expanding demand for public skiing. Due to re-occurring droughts in the U.S. Southwest, most ski areas are dependent upon artificial snowmaking techniques to counteract the problem of insufficient snowfall during the winter season (Leao and Tecle 2003). As a solution to insufficient snowfall, about 59 percent of the ski resorts in the United States produced and used artificial snow in 1984 (Kocak and Van Gemert 1988). The percentage of ski resorts using artificial snow increased to 91 percent in 2003 (Leao and Tecle 2003). The major concern on the use of artificial snow in the Arizona Snowbowl or elsewhere has been its possible impacts on natural resources (especially on soil, water, vegetation, and wildlife). However, there is little information about the intensity and severity of disturbances that may occur following the application of artificial snow made from reclaimed water. This indicates the need for a serious scientific study on the environmental impacts of snowmaking in general, and from reclaimed wastewater in particular.

The Arizona Snowbowl wants to improve the reliability and profitability of its operation through artificial snowmaking using reclaimed water from the city of Flagstaff. The rationale behind this is to ensure the continuous availability of sufficient snow on its ski facilities during the winter season to enhance their carrying capacity and meet the recreational demands on the ski facilities. The additional work will involve making new skiing trails, installing modern chairlifts, adding snow play areas, and constructing a 14.8-mile pipeline to transport the reclaimed wastewater to on-site holding tanks. For this purpose, the USDA (U.S. Department of Agriculture) Forest Service and Coconino County conducted an environmental impact study to determine the viability and environmental effects of the proposed snowmaking from reclaimed wastewater project.

In 2005, the Coconino National Forest permitted the Arizona Snowbowl to implement the proposed actions in the ski area. The proposal consists of using up to 1.5 million gallons per day of reclaimed water for artificial snowmaking from November to the end of February, whenever there is inadequate snow for skiing. However, 10 native tribes are opposing the use of reclaimed water for snowmaking on the San Francisco Peaks because they consider the peaks to be sacred and argue that the use of reclaimed water for snow will have negative impacts on the spiritual and cultural values of the Peaks as well as the vegetation and wildlife on it (Flagstaff Activist 2006). On the other hand, the Arizona Snowbowl's existence fully depends upon sufficient snow for skiing and that cannot be fulfilled by natural snowfall with the ongoing drought and increased usage. Annual visits to the ski area have increased by 157 percent over the past 20 years (Coconino National Forest 2005). Currently, the Arizona Snowbowl has 32 ski runs and 4 chairlifts (Arizona Snowbowl 2005).

Application of man-made snow, construction of ski runs, and subsequent use of these pistes (runs) by skiers have substantial impacts on soil, vegetation, and wildlife. This is so because ski slopes are machine graded and machine leveled and the addition of water and nutrients will have substantial impact on the vegetation. Ruth-Balaganskaya and Myllynen-Malinen (2000) found that ski slope construction is one of the major anthropogenic factors responsible for ecosystem degradation in mountain areas. Therefore, though snowmaking can provide many benefits to the economy of Flagstaff, there are various concerns about possible adverse impacts on the ecosystem of the San Francisco Peaks.

STUDY AREA

The Arizona Snowbowl is located 23 km north of Flagstaff within the Coconino National Forest

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and on the San Francisco Peaks (Figure 1). Three sides of the Arizona Snowbowl are surrounded by the 7533.62 ha Kachina Peaks wilderness area. At present, the size of the skiing area is 83 ha. The elevation of the skiing area ranges from 2789 m at the base to 3670 m at the top.

The climate of the San Francisco Peaks is mainly characterized by winter and summer precipitation regimes and spring and fall drought cycles. The soil type of the Peaks is primarily loamy. The Rocky Mountain Subalpine Conifer Forest and Woodland within Engelmann Spruce–Subalpine Fir series is the predominant biotic community in the Snowbowl area. In this community, the dominant forest type is corkbark fir (*Abies lasiocarpa*; Coconino National Forest 2005). The potential tree species of the Snowbowl area are Douglas-fir (*Pseudotsuga menziesii*), limber pine (*Pine flexilis*), Aspen (*Populas tremuloides*), corkbark fir (*Abies bifolia*), and some Engelmann spruce (*Picea engelmannii*). The grasses and forbs comprise mainly fescue (*Festuca* spp.), squirrel-tail (*Sitanion hystrix*), orchard grass (*Dactylis glomerata*), wheat grass (*Agropyron trachycaulum*), deers-ears (*Swertia* sps.), and silverleaf cinquefoil (*Potentilla anserina*).

The Snowbowl area also seems to be a very important habitat for various wild animal species. According to a list of threatened, endangered, and sensitive species in the Mormon Lake and Peaks Ranger District in July 2002, there are two federally listed threatened wildlife species in the Snowbowl area—the Mexican spotted owl (*Strix occdentalis lucida*) and the bald eagle (*Haliaeetus leucocephalus*).

METHODS

The primary sources of information for this study were an extensive review of the literature and interviews and written communications with concerned officials and experts in the study area. We used published and unpublished data and other information on snowmaking and its effects on the biotic and abiotic communities, as well as various articles, research papers, EIS reports, theses, books, and online media to make inferences about the impacts of applying artificial snow made from reclaimed water on ecosystem biodiversity and other environmental conditions in the Arizona Snowbowl area.

RESULTS

The reclaimed water produced by the city of Flagstaff's Rio de Flag Wastewater Treatment Plant (RFWTP) has an A water quality rating, because compared to the national drinking water standards (Van der Leeden et al. 1990), the quality of the water with respect to many parameters (except coliform bacteria) is very good. According to the Arizona Department of Environmental Quality (ADEQ), such reclaimed water with an A rating is suitable for snowmaking (Coconino National Forest and Coconino County 2005). However, because the maximum allowable amount of bacteria in drinking water is 1.0 CFU/L (colony-forming units per liter), reclaimed water with values slightly above the maximum level (counts of about 2.0 CFU/L; Van der Leeden et al. 1990) is considered unsafe for drinking. It is also important to note that the pH of the precipitation around Flagstaff ranges between 5.0 and 5.5; this is relatively acidic compared to the pH level of 7.0–7.8 of the reclaimed water (Van der Leeden et al. 1990).

Laboratory tests of water samples from different Flagstaff water supply wells and the Rio de Flag Wastewater Treatment Plant show the presence of various chemical compounds. The values for these compounds in the reclaimed water are higher than in the water samples from the wells, as shown in Table 1.

Concerning cloud seeding, an experiment conducted by Knight et al. (1979) suggests that the prolonged snow cover due to winter cloud seeding may increase the productivity of dry meadows vegetation. Such an experiment was performed in southeastern Wyoming. Treatment and control plots were established separately in dry sites and in mesic sites. In the treatment plots, snow cover was prolonged by winter cloud seeding. Researchers found an increase in the dry weight of the vegetation particularly in dry sites compared to mesic sites.

In a study conducted in Switzerland, Kammer (2002) examined the floristic changes in subalpine grasslands after 22 years of artificial snowmaking. The results showed substantial changes in floristic composition of vegetation due to the subsequent use of man-made snow. Particularly, the additional availability of water and ions in man-made snowmelt brought changes in the vigor and composition of the vegetation communities. The study also showed that faster-growing species with nutrient-rich characteristics could grab more additional nutrients from snow melt than the species with low nutrient characteristics. The chart in Figure 2 shows changes in floristic composition in the study sites after 22 years of artificial snow application. In the same study, the researcher also tested the properties of river water, artificial snow, natural snow, and precipitation, and found that

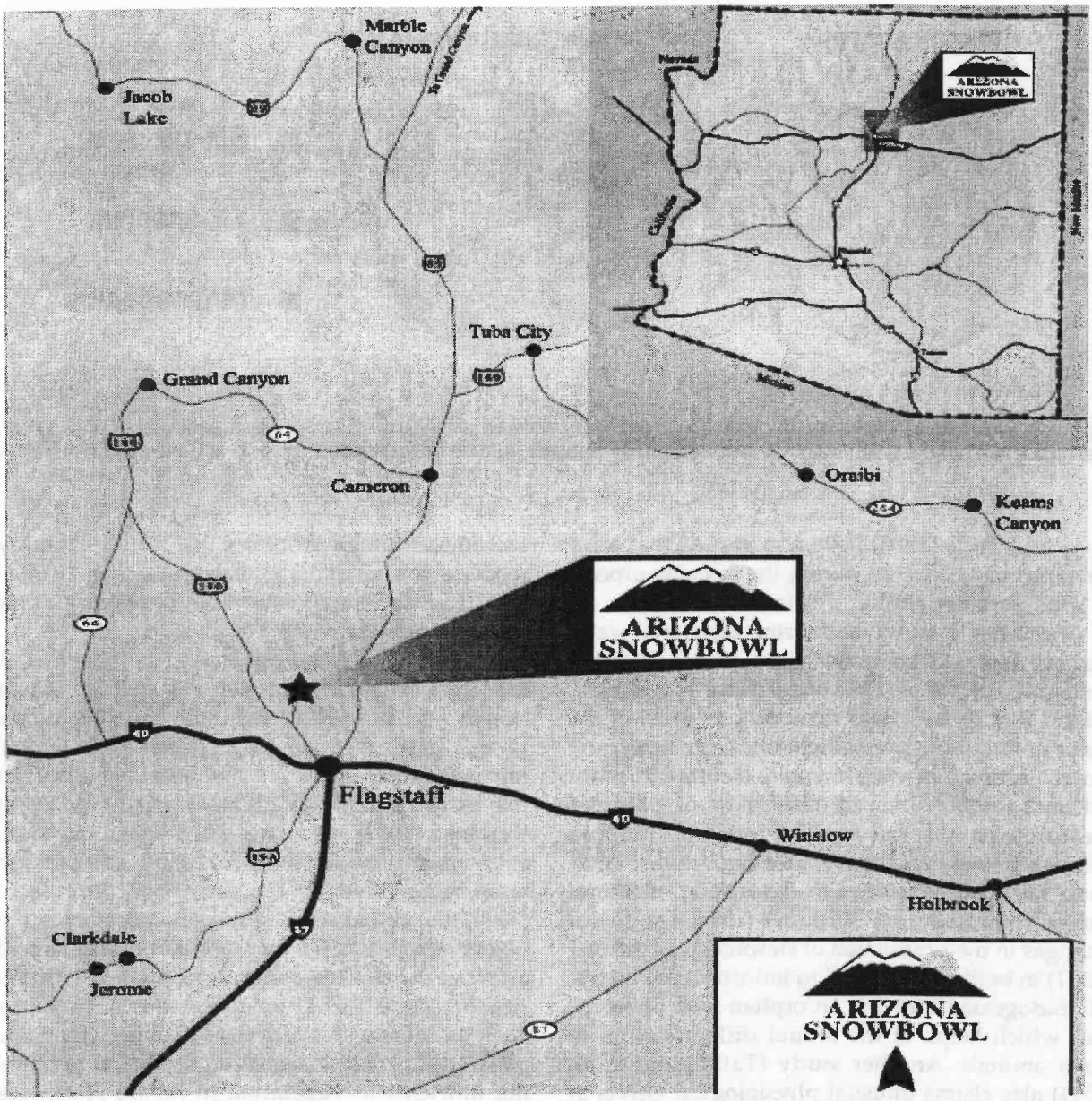

Figure 1. Location map of Arizona Snowbowl (Coconino National Forest 2005).

artificial snow has higher pH, calcium, ammonium, and nitrate concentrations than natural snow, as shown in Table 2.

DISCUSSION

The main items to consider when looking at the effects of using artificial snow from reclaimed water are pH, nutrient contents, and durability of the snow. These items can affect the use of reclaimed water to make snow at ski areas such as the Arizona Snowbowl. Currently, there is little information available on the impacts of reclaimed water on the ecosystem even though it is used for various purposes all over the world. For example, reclaimed water is used for watering golf courses and landscapes alongside roads and public parks, and also for cooling power-generating plants (USGS 2006). The main concerns regarding the use of reclaimed water for making snow are related to pH and bacterial concentration. However, a lab test showed that the pH of the reclaimed water is almost equal to that of drinking water (Van der Leeden et al. 1990) while harmful bacteria are killed using ultraviolet radiation and chlorination.

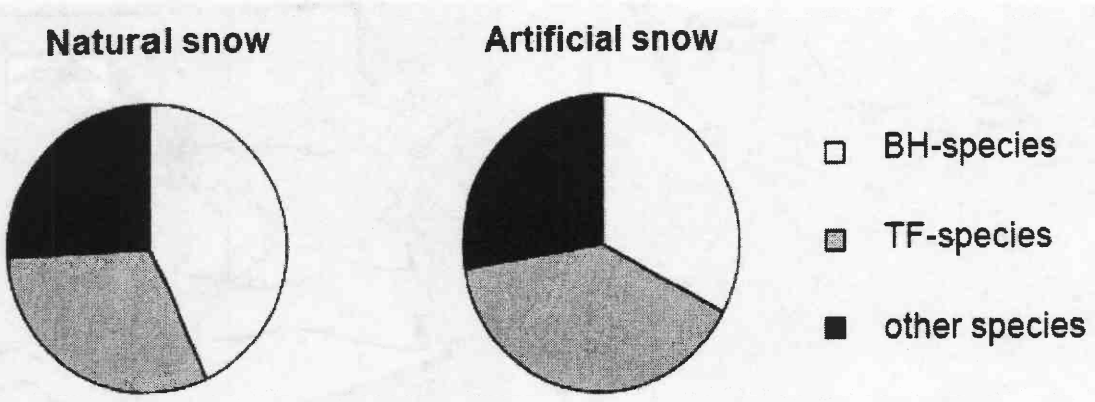

Figure 2. Changes in vegetation composition in artificially snowed plots (1 sq m) of dry hay meadows of the *Bromus/Helictotrictron* type, nutrient-rich hay meadows of TF species, and other nonspecific species in Savognin, Switzerland.

Leao and Tecle (2003) have also argued that some bacteria may be killed during the freezing process at a temperature of 0° C or below.

Nutrients in snow made from reclaimed water do not seem to be major risks to wildlife that consume such snowmelt water. Glassmeyer et al. (2005) found that the concentrations of 35 of the most commonly detected chemicals in water are much higher in wastewater treatment plant effluent samples than in other parts of a stream. Research on the red-spotted newt by Propper (2004) showed that the animal's ingestion of common pesticides resulted in disruption of pheromonal communication. Propper (2004) also found changes in the production of steroidogenic factor 1 (SF-1) in bullfrogs exposed to industrial pollutants. Steroidogenic factor 1 is an orphan nuclear receptor, which helps in the sexual differentiation of such animals. Another study (Tatarazako et al. 2004) also claims unusual physiological effects in some aquatic animals, algae growth, and ecosystem functions. These happen partly due to the presence of some toxic ingredients like triclosan in the wastewater, although the exact and specific reasons for such changes still remain to be studied.

In another study, Sheikh et al. (1998) tested the use of tertiary-treated reclaimed water for irrigation. Their research agrees with others who have found that tertiary-treated reclaimed water is safe and can be used to irrigate food crops. Laboratory tests of reclaimed water have not shown a significant presence of the pathogenic microorganisms of concern, such as *E. coli*, Cyclospora, and Salmonella, which would affect food safety. In this particular case, the Rio de Flag reclaimed water is far better than most treated wastewater because it is reclaimed through processes that include primary, secondary, and tertiary treatments, and disinfection (Rio de Flag Wastewater Treatment Plant, based on personal visit).

The presence of nutrients such as calcium, sulfur, and phosphorus has some impact on vegetation as well as wildlife including aquatic animals. In this case, fast-growing species with higher nutrient intake capability get some benefit from the extra nutrient availability (Kammer 2002). Kammer (2002) also suggested that man-made snow makes species that like high-nutrient water more competitive. On the other hand, Rixen et al. (2004) found that some species that are capable of higher nutrient intake were avoiding ski runs with artificial snow. This contradiction may be due to site characteristics or human-induced disturbances such as the various physical activities that take place on ski runs. Research on the effects of applying nutrients to vegetation in inland Northwest conifer stands found that multi-nutrient fertilization was beneficial to overstory as well as understory vegetation. The study also revealed that such an increase in nutrient concentration is very good for wildlife because it helps produce very nutritious plants (VanderSchaaf et al. 2004).

The availability of additional water in the ski areas is one more important item to consider, since 60 cm of artificial snow cover provides approximately 200 liters of water per square meter (Mosiman 1999, cited in Rixen et al. 2004). This additional water is very beneficial to plant species, especially those that grow in dry areas (Knight et al. 1979). Through this experimental work, Knight et al. (1979) found an approximately 50 percent increase in the dry weight of dry area vegetation

Table 1. Presence of pharmaceuticals and other compounds in Flagstaff well water and the Rio de Flag Wastewater Treatment Plant's water (in micrograms per liter).

Compound	Woody Mtn Well 9	Continental Well 2	Treatment Plant Discharge	Filtered vs. Unfiltered
1,4-dichlorobenzene	< 0.5	< 0.5	E 0.2	F
3,4-dichlorophenyliso-	< 0.5	E 0.1	E 0.1	U
4-nonylphenol	< 5.0	< 5.0	E 0.1	U
9,10-anthraquinone	< 0.5	< 0.5	E 0.1	F
AHTN	< 0.5	< 0.5	3.0	F
Benzophenone	< 0.5	< 0.5	E 0.1	F
Benzophenone	< 0.5	< 0.5	E 0.1	U
Bromacil	< 0.5	E 0.4	< 0.5	U
Caffeine	< 0.5	< 0.5	E 0.1	F
Caffeine	< 0.5	E 0.1	E 0.1	U
Cholesterol	< 2.0	< 2.0	E 0.1	U
Ciprofloxacin	< 0.005	< 0.005	0.356	F
DEET	< 0.5	E 0.1	E 0.2	F
DEET	< 0.5	E 0.1	E 0.2	U
Diethoxynonylphenol total	< 5.0	E 0.1	E 0.1	U
HHCB	< 0.5	< 0.5	0.5	F
HHCB	< 0.5	E 0.1	E 0.4	U
Indole	< 0.5	< 0.5	E 0.1	U
Isochlorotetracycline	< 0.01	0.01	< 0.01	F
Phenol	E 0.2	0.7	E 0.2	F
Phenol	E 0.3	E 0.2	2.9	U
Prometon	< 0.5	E 0.1	< 0.5	U
Sulfadiazine	< 0.005	< 0.005	0.472	F
Sulfamethox-axole	< 0.005	< 0.005	1.09	F
Tetracycline	0.09	< 0.01	0.16	F

E = estimated; AHTN and HHCB refer to polycyclic musks; DEET (N,N-diethylmeta-toluamide) = insect repellent gradients.

Table 2. Comparison of ion contents (mg/l) and pH of (1) water from Gelgia River used for making artificial snow in Savognin, (2) fresh artificial snow at Savognin, (3) natural snow at Savognin, and (4) natural precipitation on Rigi Mountain, central Switzerland (from Kammer 2002).

Contents	(1) Gelgia River Water	(2) Artificial Snow	(3) Natural Snow	(4) Natural Precipitation
pH	—	8.52	4.90	4.81
NO_3	1.80	1.80	0.95	1.86
NH	0.05	0.05	0.05	0.72
Na	2.40	—	—	0.11
Mg	—	3.90	0.03	0.03
PO_3	0.008	0.005	0.06	—
SO_4	47.0	—	—	1.20
Cl	1.00	—	—	0.16
K	0.70	—	0.18	0.04
Ca	—	7.4	0.50	0.30

watered with artificial snow compared to plants watered with natural snow, but the experimental result also showed a decrease in the dry weight of vegetation growing in mesic sites that use artificial snow. As Arizona has been suffering from continuous drought over the past few years and is characterized by a drier climate with low humidity, the vegetation in the Arizona Snowbowl would get more benefit from the additional moisture from the snowmaking. Such additional water availability also provides more moisture to support more wildlife. Furthermore, Knight et al. (1979) argued that this condition may lead to more water entering the soil, helping with litter decomposition (Webber et al. 1976) and mineralization as well as an increase in nutrients leaching into the soil. On the other hand, researchers note that application of man-made snow can delay spring season vegetation growth, leading to a delay in the growing season (Rixen et al. 2004; Wipf et al. 2002). For example, Kammer and Hegg (1990, cited in Kammer 2002) reported that late-flowering species remained blooming until the end of June on the areas covered with artificial snow, while the plants on the natural snow covered areas were already fruiting. This delaying effect may be an important concern with regard to forage availability for wildlife at Arizona Snowbowl. This particular factor may compel mammals and other big game animals to move away from the Snowbowl area.

Another effect of applying man-made snow is its ability to stay longer in the ski run sites as compared to natural snow. Seed-producing trees may experience significant negative effects from the prolonged snow cover, which definitely delays the development of seed germination and seedling production, hence resulting in possibly lower amounts of vegetation cover in some areas. Walker et al. (1999) mentioned that the delay in the start of the growing season due to an artificially increased snow cover caused extensive dying of *Kobresia myosuroides*, a species that is adapted to thin winter snow cover of alpine tundra. The composition of fir and other associated seed-producing species will be affected in the case of the Arizona Snowbowl and will provide more space for other vegetation or any other invasive species to grow.

Artificial snow also has some negative impacts on soil, as it can cause severe soil frost in the soil crust. The densely compacted snowpack decreases gas permeability, leading to an elevated CO_2 concentration in the soil. This situation is not good for some vegetation communities because it may result in lowering the frost resistance of some sensitive species (Newesely et al. 1994, cited in Wipf et al. 2005).

After snow production, snow grooming is necessary to level and manage the ski runs. Various researchers have suggested that ski trail grooming also has other impacts on the vegetation regime in the area (Rixen et al. 2004; Pickering et al. 2003; Wipf et al. 2005). Wipf et al. (2005) have found lower species richness and productivity on ski piste plots. They also noted lower abundance and cover of woody plants and early flowering species. Rixen et al. (2004) observed the same results in their study.

As discussed earlier, the pH content of artificial snow is higher than that of natural snow. However, that observation was made using man-made snow produced from river or ground water. In the Arizona Snowbowl case, snow will be produced from reclaimed water. Therefore, there is no information available about the pH content or the nutrients that will be present in the snow made from reclaimed water. We can only assume that the properties of the snow produced in the Arizona Snowbowl will have at least the same properties as the snow produced from river or ground water sources. The argument in support of this view is that the treated wastewater at the Rio de Flag Treatment Plant is class A reclaimed water with standards as good as river water. Also, the only major distinctions in quality between the reclaimed water and drinking water are slight differences in pH and bacterial concentration. The higher pH value may cause some alteration in the physiological characteristics of vegetation. As some research reveals, the higher pH may change plant bodies from acidic to basic, or slowly and gradually make basophilic species cover an area over the long term (Kohler 2000, cited in Kammer 2002).

On the other hand, application of man-made snow at the Arizona Snowbowl skiing area may result in more mountain front recharge and surface flow, which eventually ends up in the Little Colorado and Verde Rivers as well as recharging the underlying aquifer. The additional water in the soil and the ground will also be a good source of moisture for the vegetation and wildlife in the area during the dry season and in periods of drought. However, the higher nutrient content (Table 2) may become problematic for aquatic organisms as well as other wildlife species, although it has some benefits for algae and other plant species by helping them to spread extensively and very quickly. The presence of large amounts of such plants can

reduce the amount of O_2 available for other aquatic organisms (Purdue University 2006).

The wildlife in and around the Arizona Snowbowl may be affected by the excess nutrient availability. The extra nutrient intake may result in weight gain by some wildlife species, leading to changes in their roosting, feeding, and breeding habits. Night-time noise from snow guns may also affect the activities of the Mexican spotted owl because owls are active at night. Another school of thought however suggests that such noise might be advantageous for spotted owls because their prey—rodents and small mammals—might be disturbed and thus more visible at night.

CONCLUSIONS

The study presented in this paper suggests that artificial snow made from reclaimed water can have some moderate and manageable impacts on ecosystem biodiversity in the Arizona Snowbowl area. This is in line with previous studies such as that of Wipf et al. (2005), who concluded that artificial snow has moderate impacts on ski areas. However, we have not found any information that suggests the disappearance or elimination of any animal or plant species due to the use of artificial snow, although the presence of some threats has been argued in some studies (Rixen et al. 2004; Walker et al. 1999).

To lessen the possible impacts of man-made snow on the Arizona Snowbowl ecosystem, the nutrient content, various chemical compounds, and pH levels in the reclaimed water should be kept to the same level as that in rain or natural snowmelt water through some type of chemical treatment. Also the density and structure of the artificial snow should be maintained close to that of natural snow so that it will not last longer than natural snow on the ground. Careful periodic monitoring and evaluation of the ecosystem in the area would be helpful to note and prevent any negative impacts from applying the snow produced from reclaimed water. We also recommend that carefully designed and continuous field research should be conducted to evaluate the impacts of applying man-made snow produced from reclaimed water on the ecosystem at the Arizona Snowbowl and to help plan and develop a realistic, sustainable, environmentally safe and socially and culturally acceptable snowmaking project.

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ARIZONA CHAPARRAL: A REVIEW AND RESEARCH DATABASE

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Chaparral is a shrub-dominated vegetation type typically found worldwide growing under Mediterranean climates. It has many different names—mallee in Australia, garrigue in France, tomillares in Spain, phrygana in the Balkans, mattoral in Chile, and fynbos in South Africa. "Heath" is another term used for a similar vegetation type in South Africa and southeast France. In the United States, the term "chaparral" was initially coined to describe dense brush fields made up of broadly distributed sclerophyll vegetation located in the Upper Sonoran life zone of southern California. "Chaparral" evolved from "chabarra," the Basque word for a scrub oak of the Pyrenees (Cronemiller 1942), and the Spanish in California used the term "chamiso" (or "chamisal") to designate open brush areas composed of small shrubs. To early Spaniards, chaparral was the kind of brush field one could not ride a horse through, whereas chamiso or chamisal (or later just chamise) referred to more open brush stands dominated mainly by chamise (*Adenostoma fasiculatum*). Arizona chaparral has been termed "mock " or "interior" chaparral because it does not grow in a characteristic Mediterranean climate.

Chaparral in Arizona largely occurs on rough, discontinuous mountainous terrain south of the Mogollon Rim, extending approximately from Seligman in the northwest to the Chiricahua Mountains in the southeast. Most of the chaparral type in the southern Rocky Mountains is located in Arizona. Estimates of chaparral acreage in Arizona vary from about 3 million acres (1.2 million hectares; Cable 1973) to 4 million acres (1.5 million hectares; Hibbert and Ingebo 1971) to nearly 6 million acres (2.4 million hectares; Nichol 1952). Approximately 2.2 million acres (0.9 million hectares) of chaparral in Arizona are found within the National Forest system, mainly the Prescott and Tonto National Forests, and more than 60 percent is under federal ownership or management (Cable 1957).

Chaparral makes up a significant part of Arizona's wildlands, where it provides watershed protection, wildlife habitat, recreational opportunities, and forage for livestock production. The importance of the chaparral vegetation type in Arizona has led to its inclusion in long-term research and management programs of natural ecosystems throughout the state. One such program (called the Arizona Watershed Program) was initiated in the 1950s to study the effect of vegetation manipulations on streamflow (Fox et al. 2000). This program included designating watersheds in all major vegetation types in Arizona, including mixed conifer and ponderosa pine forests, pinyon-juniper woodlands, and chaparral, as long-term research sites. Much has been learned through this long-term program about the chaparral vegetation type. Although a large amount of data and information has been collected on chaparral, it is not as widely available for use by interested parties as is the information about ponderosa pine forests.

The overview of Arizona chaparral provided here also outlines the activities underway to incorporate this body of information into a computer database to make it widely available. This database will provide present-day managers with a source of information useful for evaluating the role of chaparral management on streamflow augmentation. The increasing need to provide additional water for rapidly growing metropolitan areas in Arizona and the Southwest has prompted a renewed interest by water managers on the effect of vegetation management on streamflow.

CHARACTERISTICS

Historical Development

Although Arizona and California chaparral are similar in many respects, important differences in the vegetation characteristics of the two have evolved due to the differences in the historical

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climatic regimes of these two vegetation types. Initially, chaparral did not expand as a regional vegetation type, but instead it was an understory in woodlands (Rundel and Vankat 1989). These woodlands developed as part of a large vegetation complex found in southwestern North America during the late Paleocene to early Neogene, when the areas were subjected to a subhumid climate having summer rainfall conditions. The ancestral taxa were derived mainly from laurophyllous forests and woodlands as a result of basic adaptations of thick evergreen leaves, stump sprouting, and deep root systems. These taxa had therefore preadapted to the increasingly more stressful environments of the later Paleogene, when secondary drought-resistant adaptations such as villous leaf covering, deep crypts, thicker leaves, and a deciduous habit were important. However, these shrubs formed only small seral communities on drier sites during the later Tertiary period. The increasing aridity favored the spread of desert and other semiarid vegetation, which divided and restricted the chaparral vegetation complex to certain areas in California, Arizona, and northeastern Mexico. The development of drought throughout the summer occurred during the Tertiary period in California, which caused a shift in plant activity from summer to spring. In contrast, plants in Arizona and northeastern Mexico remained active during the summer rainy periods (Axelrod 1989). Chaparral became a regional vegetation type only in historical times as human-caused ignitions increased fire sequences, which regularly removed the tree layer and increased shrub density on many of the former woodland types.

Physical Setting

Arizona chaparral occurs mainly at elevations between 3000 and 6000 ft (about 900–1800 m), although it is found on some higher mountain peaks (Hibbert and Ingebo 1971; Pase 1966). Chaparral species can integrate with other vegetation zones, including ponderosa pine, pinyon-juniper, encinal woodland, and grassland. Factors determining which vegetation type will occur on particular sites within the overall chaparral zone are complex and involve many different combinations of topographic, geologic, climatic, and edaphic conditions.

The average annual precipitation in Arizona varies from about 15 inches (38 cm) at the lower elevations of the chaparral shrublands (3000 ft or 900 m) to over 25 inches (64 cm) at the higher elevations (6000 ft or 1800 m). Approximately 60 percent of the annual precipitation occurs as rain or snow between November and April. The summer rains fall in July and August, which are the wettest months of the year. Annual potential evapotranspiration rates can approach 35 inches (89 cm; Ffolliott and Throud 1974; Hibbert et al. 1974). The climate supporting Arizona chaparral is thus bimodal (i.e., both summer and winter precipitation occurs). Arizona chaparral is not found in the Mediterranean-type climate typical of the true chaparral found in California and elsewhere throughout the world, characterized by a lack of summer rainfall and a long period of moisture stress.

Chaparral soils are typically young, coarse-textured, deep, and poorly developed lithosols. Granites occur on more than half of the shrublands in Arizona, although some stands are found on schist, diabase, and sandstones (Hibbert et al. 1974). Despite having shallow A and B horizons, the C horizon can be deep and is hydrologically important, with total porosities of 20–25 percent. The topography is characterized by mountain ranges dissected by steep-walled gorges, and canyons with slopes of 60–70 percent are common. Chaparral vegetation can be found on all aspects.

Although some areas of Arizona chaparral receive over 25 inches of yearly precipitation, streamflow in most channels is ephemeral or intermittent. The high evapotranspiration rates associated with a deep-rooted shrub canopy usually deplete most of the available soil moisture, so little is usually available for streamflow. Streamflow typically occurs during intense summer rains or during periods of rapid snowmelt in the spring. The dense brush canopy of Arizona chaparral found in areas of higher precipitation usually provides excellent soil protection with little or no runoff; therefore, erosion is limited to moderate rates even on the steep, dissected topography. However, frequent wildfires during the spring, summer, and fall months can completely denude the watersheds of their protective cover and, in doing so, drastically change the hydrology of the affected watersheds. After fire, even small amounts of rainfall can cause large amounts of runoff and erosion to occur. The high runoff and erosion rates result from the loss of the protective plant cover and the production of a water-repellent soil condition during the fire. These high erosion rates usually persist until the native shrub cover becomes reestablished.

Vegetation

Chaparral communities typically consist of "moderate to deep-rooted" evergreen (sclerophyllous) shrubs that attain maximum development on deeply weathered or fractured rock mantles and deep soils (Hibbert et al. 1974). The density of the shrub canopy varies from very sparse, open stands of brush to dense, almost impenetrable stands, depending on local climate and site conditions. Sparse brush stands are commonly found on areas receiving lower amounts of precipitation and southern aspects, while the densest stands receiving 25 inches or more of annual precipitation are located on northern and eastern aspects.

An interior chaparral zone is located between the desert shrubs and high forest, where shrubby and stunted tree communities, dominated by many species of unrelated taxonomy, exist as a single ecological type (Cooper 1922). As a result, Arizona chaparral is sometimes called the "in-between" biome because it grows between desert and grassland, or forest and grassland, and shares certain characteristics with all these biomes (Ricciuti 1996). Chaparral and encinal woodlands occur in mixtures adjacent to ponderosa pine stands on the slopes of isolated mountain ranges.

All the major shrub species are well adapted to periodic fires, meaning that they either sprout prolifically from the root or root crown and do not produce many seedlings (Pase 1969), or they produce abundant seed and do not sprout. Both mechanisms are used to quickly restore the shrub cover following fire. Depending on the site, the shrub species usually dominate within 30–40 years and are again subject to recurring fire. Chaparral stands consist of a heterogenous species mix in many locations, but often only one or two species dominate. Shrub live oak (*Quercus turbinella*) is the most prevalent species, with true (*Cercocarpus montanus*) and birchleaf (*C. betuloides*) mountain mahogany, Pringle (*Arctostaphylos pringlei*) and pointleaf (*A. pungens*) manzanita, yellowleaf (*Garrya flavescens*), hollyleaf buckthorn (*Rhamnus crocea*), desert ceanothus (*Ceanothus greggii*), and other shrub species also included in the chaparral mixture of shrub species. Annual and perennial grasses, forbs, and half-shrubs are present, particularly where the overstory canopy is open or only moderately dense. Stream channels often support a variety of oak trees (*Quercus* spp.) on the drier sites and can on occasion support true riparian vegetation in higher precipitation areas where near-perennial streamflow occurs (Brown 1978).

USES AND VALUES

In the past, Native Americans probably used plants and animals in chaparral areas for their sustenance. Later, mining and cattle ranching were important activities in chaparral areas for well over a century (Bolander 1986). Both silver and gold were mined throughout the chaparral areas in Arizona. Cattle grazing of chaparral stands was started in central Arizona around 1874 and within a single decade the vegetation type was almost entirely stocked or overstocked. Extremely high early stocking rates led to the disappearance of grasses in many chaparral stands, thereby increasing the cover and density of shrubs.

Chaparral continues to provide watershed protection on millions of acres of steep, deeply incised mountainous terrain in Arizona. In many cases these brush-clothed watersheds are immediately adjacent to urban development, and concerns about protecting the urban-wildland interface from wildfires have long been recognized and are continually increasing over time (Hickman 1987). Grazing is still important in some areas, and rangelands are often grazed year-long by livestock, because evergreen plants common to the shrublands provide a continuous forage supply in addition to understory grasses that remain or have been seeded. A variety of wildlife species (including some threatened and endangered species) are found in chaparral shrublands, with comparatively high populations often being concentrated in fringe areas. Although the recreational value (e.g., hiking, camping, and hunting) of chaparral may be considered lower than for the higher elevation vegetation types, the close proximity to major population centers insures heavy utilization for recreational purposes.

HYDROLOGIC RESEARCH AND APPLICATION

Research Activities

Long-term hydrologic research in the chaparral vegetation type was conducted as part of the Arizona Watershed Program, which evaluated the potential for augmenting streamflow by means of vegetation management (Fox et al. 2002). The research in chaparral was conducted throughout Arizona, but several specific studies were located on long-term experimental watersheds that represented environments extending from high precipitation sites near Lake Roosevelt on the Salt River north of Phoenix to drier sites located on Mingus

Mountain north of Prescott. These watersheds were instrumented for streamflow and climatic measurements, with data on some sites being collected for 30 years or longer. The effects of brush-to-grass conversions on streamflow response were investigated in depth because this treatment was shown during preliminary studies to potentially increase streamflow (Hibbert et al. 1974). In addition to the research conducted on permanent watershed sites, a large number of related studies were conducted on chaparral areas throughout Arizona.

To evaluate the effects on streamflow augmentation, brush control and conversion to grass were effected on the permanently established watersheds by the use of herbicides and prescribed fire, or combinations of the two. Additional studies of brush control on other sites included grazing by goats and mechanical methods, while numerous other studies on the chaparral type focused on wildlife, ecology, recreational aesthetics, postfire regeneration, and economic aspects of chaparral management. The research program ended with the results being applied to a large watershed demonstration project located on the Prescott National Forest.

Research Results

Much has been learned about Arizona chaparral over the years, although little research is currently being conducted. The past research focused on hydrologic processes in chaparral areas, showing that chaparral is a major source of streamflow if brush control can be achieved. It was found that replacing deep-rooted shrub plants with shallower-rooted grasses resulted in substantial increases in streamflow, particularly if the treated areas were located on the lower slopes near the stream channels. Brush control research was conducted using mechanical, chemical, and biological methods, as well as prescribed fire. Chemical control was most effective, but environmentally least desirable. Mechanical control was limited to small areas on relatively gentle slopes. Biological control with goats was limited because of the lack of interest in meat and wool products. Prescribed fire was effective for maintaining existing brush-to-grass conversion, but was not too effective for the initial conversion. However, when brush fields were converted to brush-grass mosaic patterns where more than half of the brush cover had been converted to grass, water was increased, wildlife habitat was improved, and there was increased grazing for domestic livestock (Hibbert 1986).

The long-term research data collected on the experimental watersheds includes daily streamflow records, climatic data, and regular vegetation inventories. Much of this field data remains in summarized form as part of the Rocky Mountain Research Station's historic data files. Although the results from many of these studies were published in scientific outlets, some information still remains as project progress reports and other unpublished documents. State-of-the-art summaries for several major topics of the chaparral research program were published in 1974 and 1975. These include watershed management (Hibbert et al. 1974), economics (Brown et al. 1974), and range management (Cable 1975), and research accomplishments on individual research areas in chaparral and other vegetation types studied as a part of the Arizona Watershed Program have also been summarized (Baker 1999). A more comprehensive summary of the program (including an annotated bibliography, long-term data file system, and published monographs) is now being planned as described below.

DATABASE DEVELOPMENT AND AVAILABILITY

Although a wealth of information from field research on Arizona chaparral exists, much of this information is not readily available, nor are recent comprehensive summaries of this information available. Efforts are currently being focused on summarizing all research findings and data and integrating this information into the existing watershed database, "Watershed Management in the Southwest" (http://www.ag.arizona.edu/OALS/watershed). This database includes a variety of topics on watershed management practices, displays accessible baseline data sets, and provides an interactive learning package on watershed management practices (Baker and Young 2000; Haseltine et al. 2002). This website is an ongoing International Arid Lands Consortium demonstration project. Recent efforts include GIS applications to allow users to search, chart or graph, and compare precipitation, streamflow, vegetation, and other watershed-based resource characteristics through a dynamic interface.

The website has proven useful to many people desiring this kind of information. Watershed managers throughout the world are formulating and implementing actions that result in the manipulation of natural and human resources to satisfy specific goals and objectives. Watershed management in the southwestern United States is particularly challenging because water supplies

and associated resource productivity levels are limited. In addressing this challenge, watershed management research has led to a better understanding of the hydrology, ecology, and land-use potentials of the region's watershed landscapes. This research has helped in the establishment of management guidelines to meet the needs of the growing population, but the findings obtained are not necessarily widely known or readily accessible.

Most of the bibliographic materials describing Arizona chaparral have been identified, collected, and referenced. Individual annotations of these publications are being prepared for incorporation into the Watershed Management in the Southwest database. This bibliographic information will be brought together to provide an up-to-date synthesis of our current knowledge about Arizona chaparral. This information will be presented both as a scientific review and in a management format. Other watershed data (including long-term hydrologic records collected on chaparral watersheds) will also be formatted and entered into the watershed information database in a form similar to that currently available for ponderosa pine forests (Haseltine et al. 2002).

SUMMARY

Evergreen (or sclerophyllus) brushlands occupy large areas in Mediterranean climates throughout the world. Chaparral in the Southwest is typically found in the Upper Sonoran life zones in southern California and Arizona. Chaparral vegetation in Arizona is found mainly on the rough, discontinuous mountainous terrain south of the Mogollon Rim where it covers 3–6.5 million acres (about 1.3–2.4 million hectares). Arizona chaparral provides a protective cover for steep, erodible topography and as such provides an important source of water for streamflow. Much has been learned about Arizona chaparral during the last half century. However, this information is widely spread throughout the literature. Current efforts to bring this published information into a computer database for interested users will greatly enhance not only management but future research efforts concerning interior chaparral ecosystems.

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PIECES OF THE REVITALIZATION PUZZLE: A LA COSTA DE HERMOSILLO CASE STUDY

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Restoration of desertified land is a challenge faced throughout the semi-arid and arid world. One such area in need of revitalized biotic and economic production is La Costa de Hermosillo, located in the state of Sonora, Mexico. Due to salt water intrusion of the aquifer—a result of the intensified agricultural production that began in 1945—about 80,000 ha of agricultural fields are currently abandoned. Future management options for La Costa de Hermosillo should account for biophysical, political, and socio-economic issues. This can be achieved by utilizing a participatory community development philosophy and appropriate technology techniques. Also, lessons should be learned from case studies in other semi-arid and arid areas of the world, and collaboration with scientists dealing with similar land management issues in other countries should be encouraged.

STUDY AREA

La Costa de Hermosillo is in the western section of a coastal plain near the center of the Sonoran Desert and is situated between the coast of the Gulf of California and the city of Hermosillo, Sonora, Mexico. The mean annual temperature of this region is 22° C, with maximums above 46° C and minimums close to, but staying above 0° C. Annual precipitation is in the range of 100–225 mm. The soils are extensive alluvial deposits with a mixed structure of clay, silt, and sand (Castellanos et al. 2005). The natural vegetation of the region consists of the central Gulf coast and plains of Sonora subdivisions within the Sonoran desert scrub formation (Shreve and Wiggins 1964).

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La Costa de Hermosillo's Agricultural Land

Irrigated agriculture started in the area in the early 1940s with diversion of small quantities of water from the Rio Sonora to irrigate plots of corn, wheat, cotton, and beans (Moreno 1994). After a dam was built upsteam on the Rio Sonora, which decreased the flow of water for crop production, the people of La Costa de Hermosillo dug wells and tapped into an unconfined aquifer (Halvorson et al. 2003). The pumped water from the aquifer was not considered to be a limiting resource during the period of intense agricultural growth from 1945 to 1970. However, the combined impacts of a salt-water contaminated aquifer, soil salinization, an unstable economy, and poor policy were too taxing on both the land and the individual farmers. Therefore, 80,000 ha were abandoned. Of all the rehabilitations programs suggested for La Costa de Hermosillo's aquifer, none mention alternatives for these abandoned fields, which range in size from 1000 to 5500 ha (Halvorson et al. 2003; Castellanos et al. 2005).

Management Options

Halvorson et al. (2003) used the La Costa de Hermosillo case study to demonstrate how sustainable land use requires an awareness of ecological signals. When ecological signals are recognized, detrimental land management activities can be modified before ecosystem components reach severe degradation. This was not the case for the 80,000 ha of abandoned land in La Costa de Hermosillo. Some researchers have concluded that salt-water intrusion into the Valley of Hermosillo aquifer is an irreversible consequence (Steinich et al. 1998). Others acknowledge that reversing such great environmental degradation is neither simple nor well defined, but recovery is possible if future management decisions consider the biophysical, political, and socio-economic components of the

situation (Halvorson et al. 2003). The following sections discuss pieces of La Costa de Hermosillo's revitalization puzzle. Participatory community development, appropriate technology, interdisciplinary dialogue, and international collaboration are four pieces that will serve as a foundation for the revitalization of both biotic and economic production.

PARTICIPATORY COMMUNITY DEVELOPMENT

The complex task of revitalizing degraded land must center on the people most affected by the degradation, in this case the farmers. Ecosystem restoration projects in other semi-arid and arid parts of the world have successfully applied a development philosophy called participatory community development. This philosophy is part of a family of approaches and methods that enable people to share, enhance, and analyze their knowledge of life and conditions, to create plans for the future, and to act on these plans (Chambers 1994).

Participatory development works because farmer's fields are the stage where ecological, social, and economic influences intersect. Therefore, farmers are most likely the best integrators of these factors (Haggar et al. 2001), and they will have good insight on which management components are most feasible in light of these factors. Representatives from surrounding communities (e.g., indigenous groups, non-governmental organizations, education and research institutions) can provide a diversity of ideas; however, the farmers are the main stakeholders and decision makers. For example, through participatory development, community members can reach consensus on income-generating projects, the integration of traditional knowledge, ecotourism possibilities, and environmental education curricula that are feasible for La Costa de Hermosillo.

APPROPRIATE TECHNOLOGY

The sustainability of any management option is dependent upon available resources. These resources might include components such as physical material, labor, and money. Whether the goal is to harvest rainwater, increase soil organic matter, or construct buildings, appropriate technology facilitates improvement over past technologies while at the same time insuring that the advancement is applicable and feasible for a specific use and setting. For example, technologies such as drip and pivot irrigation can improve water-use efficiency and decrease salinization while maintaining or increasing yields (Tilman et al. 2002). For an improved irrigation system to be appropriate, the material components and labor should be available locally and the system must be suitable for the water source, water quality, and topography of a specific site.

INTERDISCIPLINARY DIALOGUE

A return to an intensive agricultural system is not a realistic option for La Costa de Hermosillo's degraded land. Any single and extensive use of the land will most likely be unsustainable. However, representatives from a variety of disciplines (e.g., economists, agronomists, sociologists, engineers) can provide the farmers with a set of options for revitalizing both the land and the local economy. Options might include various forms of revegetation, small-scale income-generating enterprises, and technological advancements.

For example, in a World Resources Institute paper presenting ideas for improving irrigation management in Mexican agriculture, Puebla and El-Ashry (1989) suggest that the reintroduction of salt-tolerant and drought-tolerant native vegetation is one alternative to land abandonment. They list several species that fit this criteria and provide potential marketable properties. For example, *Amaranthus hypochondriacus* is a dryland-adapted crop with value as both a nutritious food and an ornamental.

INTERNATIONAL COLLABORATION

The above paragraphs describe revitalization pieces that encourage an active exchange of information between farmers, scientists, various community members, and local government agencies. Scientists from other countries who are involved in similar land-management decisions can also provide additional advice. In fact, more research centers are acknowledging the benefits of international collaboration when dealing with issues such as those faced in La Costa de Hermosillo, and any future management plan can be improved by recognizing lessons learned abroad and through consultation with individuals in other countries.

CONCLUSION

Land degradation and abandonment is detrimental on a number of levels. Farmers are left demoralized (Puebla and El-Ashry 1989), communities are stripped of their economic foothold, and ecosystem processes require healing. Furthermore, upon abandonment, the ecosystem often retains very little, if any, economic or social value. Re-

habilitation of the land is generally not pursued (Castellanos et al. 2005). Agricultural systems in arid ecosystems are particularly fragile, as exemplified in the La Costa de Hermosillo case study. As described in this paper, revitalization of the land requires a number of pieces, including participatory community development, appropriate technology, interdisciplinary dialogue, and international collaboration. These pieces are only a few in a complex puzzle, but they can serve as a framework for eliciting additional pieces. At this point the final picture is unclear; however, beginning with a broad set of approaches proven to be beneficial in other revitalization projects is the first step toward sustainable natural resource management.

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LEARNING FROM TRADITIONAL WATER HARVESTERS IN THE NEGEV AND SONORAN DESERTS

Jolie A. Goldenetz[1]

The harvesting of rainwater is an essential component of life for many people living in semi-arid and arid ecosystems. These water-harvesting systems are particularly impressive when used for the cultivation of food crops. Studying traditional agricultural sites and the water-harvesting systems associated with these sites enables natural resource managers to gain insight into land management practices that promote healthy ecosystems. Both the Negev Desert of Israel and the Sonoran Desert of southern Arizona and northwestern Mexico are arid areas of the world where for centuries people have practiced traditional agriculture using water-harvesting systems; therefore, the traditional dryland agricultural sites found within these deserts are worthy of attention, especially for researchers working in hydrology and related fields. This paper introduces rainwater-harvesting technologies and presents five main categories that aid in the comparison of these technologies.

LEARNING EXPERIENCE

This last winter I traveled to Israel to learn from people working on a project titled "Ancient Desert Agricultural Systems Revived." The Nabatean people living in the Negev Desert from 200 BC to 640 AD created unique agricultural systems that captured rainwater runoff in the desert environment for household and agricultural uses (Evenari and Koller 1956). Remains of these systems are scattered throughout the southern half of Israel and Palestine, and archeologists, anthropologists, and agriculturalists are working together to understand and learn from them. Also, small communities of people, including Bedouins, Jews, and Palestinians, are currently adapting and utilizing these ancient agricultural and water-saving techniques.

Learning about ancient Middle Eastern culture and the traditional agricultural systems of the Negev Desert helped me to see the Sonoran Desert with a new perspective. Therefore, with a new appreciation for water-harvesting technology, I returned to Arizona with a desire to learn more about traditional agriculturalists and their relationship with the limited resources in the Sonoran Desert. To help remember and compare various water-harvesting technologies, I created five categories beginning with the letter S to represent the basic components of most systems: structure, system, source, scale, and soils.

WATER HARVESTING DEFINED

While approaches for augmenting water supplies have existed for centuries, the term "water harvesting" was introduced in 1963 and defined at that time as "the collection and storage of any farm water, either runoff or creekflow, for irrigation use" (Myers 1975). Since then, water harvesting has become an umbrella term describing a variety of methods for collecting and concentrating various forms of runoff (rooftop runoff, overland flow, streamflow) from various sources (precipitation, dew, perennial streams) for various agricultural and domestic purposes (Reij et al. 1988). The application of water-harvesting technology is most often found in arid and semi-arid regions where rainfall is not sufficient to sustain a good crop and pasture growth or where the risk of crop failure is very high due to the erratic nature of precipitation (Prinz 1996).

Structure of Water-Harvesting Systems

Water-harvesting systems are generally local and small scale, and they consist of three main components: the collection area, the conveyance system, and the storage facility (Prinz 1996; Oweis and Hachum 2003). The geometric structure of the system largely depends upon site-specific characteristics such as topography, the intended use, and the designer's personal preference (Brooks et al. 1997). Tanks, cisterns, or reservoirs might be used for storage of the collected water, or the soil itself

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can serve as a reservoir for a certain period of time (Finkel and Finkel 1986). Furthermore, the collection area and the conveyance system might be the same. For example, hillsides can serve as both the collection area and the conveyance system when rainwater is harvested off a downward-sloping hillside and channeled onto an agricultural field.

System of Production

As I mentioned in the introduction, water harvesting is a technology that people have used for millennia, not only in the Middle East but worldwide. Moreover, it continues to be applied worldwide. Of the numerous forms currently in existence, according to Prinz (1996) there are six generally recognized categories: rooftop water harvesting, water harvesting for animal consumption, inter-row water harvesting, microcatchment water harvesting, medium-sized-catchment water harvesting, and large-catchment water harvesing. Within each of these categories is an associated production system that provides a more stable, secure water supply for household drinking consumption, livestock watering, and/or the growing of agricultural crops. For example, rooftop water harvesting can be a smaller-scale technology used to collect rainwater for human consumption or watering household garden plants. On the other side of the size spectrum, farmers can construct large agricultural terraces, irrigated by hillside rainwater runoff, for growing fruit and nut trees. Many "in-between systems" are also used, ranging from small water-catchment areas that are channeled into reservoirs for livestock watering to the construction of mounds surrounding garden plants and trees to concentrate rainwater around root zones.

Source of Water

The amount, distribution, and variability of seasonal or annual rainfall in arid and semi-arid regions are key factors to consider when evaluating and applying water-harvesting technologies (Brooks et al. 1997). For example, in terms of agricultural production, part of the rainfall may be lost as surface runoff before reaching the root zone of the crops even where the amount of rainfall is sufficient for crop production (Reij et al. 1988). Therefore, it is important to investigate the rainfall patterns in the area, the locations of ephemeral and perennial water-courses, and the quantity and quality of ground water resources of the site. The availability of these water sources will greatly determine the structure and scale of a water-harvesting system.

Scale Suitable for a Specific Site

The amount of rainwater runoff collected on individual farm units in the Negev Desert is directly related to the size of the catchment area surrounding the agricultural fields (Evenari et al. 1982). Therefore, the larger the catchment area, the greater its total water yield. Each farm has its own well-defined catchment area that constitutes its water rights, along with drop structures, spillways, ditches, and dividing boxes, giving the farmer control over the distribution of the water on the farm (Evenari et al. 1982). These agricultural production systems are feasible only where large areas of sloping land and labor input to construct the system are available. Many smaller-scale water-harvesting technologies can be used, ranging from microcatchments for tree crops to garden systems where soil is built up around individual plants in a waffle-like pattern (Anschutz et al. 1997).

Soils of an Area

The absorption capacity of a soil type is its infiltration capacity, which is expressed as the quantity of water depth in millimeters per hour. Runoff is produced when the rainfall intensity is greater than the infiltration rate of the soil (Anschutz et al. 1997). Since surface runoff is the primary component of water-harvesting systems, an understanding of site-specific soil characteristics is necessary. For example, the loess soils typically found in the Negev Desert form a characteristic crust when wet. This crust becomes impermeable with rainfall; therefore, water runoff occurs even with light rains. Heavy, short-duration rainfall causes flash floods. The characteristics of the loess soil thus enable farmers to harvest water from hillsides even under low-rainfall desert conditions (Evenari et al. 1982). Furthermore, on sites where the soil type is sandy, water infiltrates more easily compared to clay soils. Therefore, on these sites, a rainwater conveyance system other than the soil (i.e., rooftop) might be more applicable.

The biological component of the soil crusts is also important. Microphytic communities composed of cyanobacteria, green algae, fungi, mosses, and lichens are found in the sand dunes of the northern Negev, where they stabilize the sand surface against wind and water erosion. Free-living symbiotic cyanobacteria are capable of nitrogen

fixation and are important nitrogen sources in the desert sand dunes. These biological crusts not only enhance surface water runoff, making them a key component of a rainwater-harvesting system, but they also combat desertification of arid and semi-arid ecosystems (Veste et al. 2001).

APPLICABILITY OF WATER-HARVESTING TECHNOLOGIES

The United Nations (UN) designated 2006 as the International Year of Deserts and Desertification. With this issuance, the UN hopes to raise global public awareness of deserts, disseminate methods for protecting the biological diversity of arid lands, and safeguard the knowledge and traditions of the 2 billion people affected by desertification (UN News Service 2006). The harvesting of rainwater is one such traditional practice which has the potential for improving the lives of many people living in dryland ecosystems by reducing the costs associated with raising animals and growing food (Oweis and Hachum 2003). To make traditional methods more applicable to current social and environmental needs, more information is required on agricultural crop phenology and water requirements. There is also a growing need for demonstration projects that present universal prescriptions and develop specifications for various economic, social, and climatological conditions (Brooks et al. 1997).

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A NEW APPROACH TO RIPARIAN AREA EDUCATION IN ARIZONA

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Jim Sprinkle,[5] Jeff Schalau,[6] and Chris Jones[7]

Riparian areas are called "ribbons of life" because they are considered the most productive habitats in North America (Johnson et al. 1977; Chaney et al. 1990). These areas are transition zones (ecotones) between aquatic and terrestrial ecosystems. As a result they provide habitat for species from both aquatic and terrestrial ecosystems, as well as species that are unique to these areas. In the arid western United States riparian areas are estimated to make up less than 2 percent of the total land area (Ffolliott et al. 2004). Despite their small area, Patten (1998) says that the role of riparian areas is disproportionate to their size, particularly in the semi-arid regions of North America. This is mainly due to the many functions and values of riparian areas, which promote greater vegetative and wildlife diversity because of the greater water availability relative to the adjacent terrestrial uplands. Although many people use the terms functions and values interchangeably, they differ (Walbridge 1993). Brinson (1993) described a function as the "ecological, hydrological or other phenomenon that contributes to self-maintenance." In contrast, a value is "something of worth, desirable or useful to humans" (Mitsch and Gosselink 1993). As a result, functions of riparian areas are relatively constant through time whereas the values of riparian areas have changed through time and probably will change again in the future as the needs and beliefs of society change.

Some of the most important functions provided by riparian areas (Schultz et al. 2000) are fish and wildlife habitat (water, food, shelter, cover); filtration and retention of sediment and nutrients from terrestrial upland runoff or out of bank floods; reduction of chemical inputs from terrestrial uplands by immobilization, storage, and transformation; stabilization of stream banks and buildup of new stream banks; increase in water storage and recharge for subsurface aquifers; and reduction of floodwater runoff.

Society considers riparian areas to be very important because of their multiple use values (Clary and Booth 1993). Riparian areas play a major role in improving water quality, particularly by reducing nonpoint source pollutants and increasing water quantity. The public's value of water quality protection was recognized by the Clean Water Act of 1972 (amended 1977) and the subsequent development of the Total Maximum Daily Loads (TMDL) program by the U.S. Environmental Protection Agency to regulate water pollution.

Riparian areas are also essential for many endangered and threatened species. Seventy percent of the threatened and endangered vertebrates in Arizona depend on riparian habitat (Johnson 1989). The Endangered Species Act of 1973 (amended in 1988) was passed with the objectives of conserving threatened and endangered species and monitoring all listed species.

Domestic livestock are also attracted to riparian areas (Roath and Krueger 1982) for the same reasons that wildlife prefers riparian areas: high forage availability and abundance (Pinchak et al. 1991), water availability (Ames 1977), favorable summer temperatures, and moderate terrain. Ranching today still accounts for a significant portion of the agricultural economy of Arizona (approximately 25%; Ruyle et al. 2000).

Finally, riparian areas also have aesthetic values in addition to production-oriented values. Riparian areas are considered prime locations for recreational activities such as hiking, horseback riding, cycling, fishing, hunting, swimming, raft floating, boating, canoeing, bird and wildlife watching, picnicking, camping, and off-road vehicular traveling (Ffolliott et al. 2004).

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The great number of users and diverse perceptions of the importance and proper use of riparian areas makes managing these areas very complex and a top priority in every state. In addition, significant percentages of riparian areas are considered to be in degraded and non-functional condition (Ffolliott et al. 2004; National Research Council 2002). Riparian area destruction has varied throughout the regions of the United States, with southeastern and southwestern states probably receiving the greatest impact (National Research Council 2002). Finally, the National Research Council (2002) has also suggested that the lack of information on the status of riparian areas has limited effective management and that a comprehensive assessment should be implemented.

OBJECTIVES AND ACTIVITIES

In Arizona, as in many other states, there has been an urgent need for an outreach program to inform the public about riparian areas. In response to this need, an outreach program was devised with the objective of increasing the awareness and knowledge of the public on the importance of riparian areas, the processes that take place in riparian areas, and the human alterations that these areas have endured. The three main activities undertaken to meet the objective were educational workshops in selected counties, publication of educational materials, and development of a Web-based educational module.

The intended audience for this outreach program was the general public, including farmers, ranchers, public and private land managers, watershed partnerships, recreationists, and other riparian area users. All these groups have a vested interest in riparian areas and an interest in communicating with each other to successfully maintain and restore riparian areas.

EDUCATIONAL WORKSHOPS

The general theme for the workshops was to present broad and general topics on riparian areas, although the information was developed to be pertinent specifically for the riparian areas in Arizona. The outreach program provided basic background information for people who work in or are interested in riparian areas. All workshops in the various counties had the same topics and presenters. Planning committee members who finalized the topics consisted of scientists from the University of Arizona, Arizona State University's Polytechnic Campus, and the Agricultural Research Service, along with University of Arizona Cooperative Extension county directors and agents. The final workshop agenda included the following topics:

1. Definition and Importance of Riparian Areas
2. Characterization of Riparian Areas
3. Hydrologic Processes in Riparian Areas
4. Fluvial Processes in Riparian Areas
5. Biological Processes in Riparian Areas – Habitat
6. Climatic Processes in Riparian Areas
7. Human Alterations to Riparian Areas

The first presentation provided various scientific and agency definitions of riparian areas, while further highlighting their importance with descriptions of their functions and values. In the second presentation, the basic characteristics of riparian areas were described, while also differentiating riparian areas from the adjacent terrestrial upland and aquatic systems. Wetlands and riparian areas were compared to each other. Hydrologic processes in riparian areas focused on the sources, distribution, and circulation of water on and below the earth's surface and in the atmosphere with an emphasis on their influence on riparian areas. In the presentation on fluvial processes in riparian areas, an introduction to the morphology of channels and floodplains was provided along with a description of stream processes in riparian areas. The presentation on biological processes described the riparian habitat, which is the summation of physical and biological processes occurring on several different spatial and temporal scales. In the climatic processes section, connections were made between the mechanisms that drive the climate of Arizona and the influence of climate on riparian areas. The last topic described how humans have impacted and altered riparian areas, directly and indirectly. These impacts cover a wide range of topics, mainly including hydrologic and geomorphic; agricultural; urban, recreational, and industrial; and other. The first six presentations were approximately half an hour each, and the last presentation was about an hour. The fact that the presenters had diverse backgrounds and worked with different institutions was one of the strengths of the workshops. Because one goal of the program was to provide information pertinent to Arizona's public, experts from Arizona were recruited.

Educational workshops were conducted in seven counties: Cochise (Sierra Vista), Coconino (Flagstaff), Gila (Globe), Graham (Thatcher), Mohave (Kingman), Santa Cruz (Tubac), and Yavapai (Prescott). These day-long workshops

lasted approximately 7 hours. The Cooperative Extension county agent or director was responsible for local arrangements. This was ideal because county agents/directors have daily contact with the local public and are thus aware of the individuals or groups who should attend the workshop because of their professions or interests. The public was informed about the workshops through advertisements in local newspapers, flyers, and email list-serves.

Participants were asked to provide written evaluations at the end of each workshop. These evaluations provided information on the success of the workshop in meeting our objectives. The evaluation form had three questions (Figure 1). The first focused on measuring the gain in awareness and knowledge as a result of attending the workshop. Participants indicated their knowledge level before the workshop and their knowledge level after the workshop. This was accomplished by using the stairstep method. The stair (a scale) had seven steps indicating an increase in knowledge level from zero to six. Participants placed the letter B on the step that represented their knowledge before the workshop and an A on the step representing their knowledge after the workshop.

Evaluations revealed that for the first six topics, 89 percent of the participants increased their knowledge by at least one level (Figure 2). For topic 7, human alterations, the knowledge levels of a significant portion of the participants (24%) remained the same. This indicates that workshop participants were aware of the impacts of humans on riparian areas, which was probably one of the reasons that the participants attended the workshop. Overall, the most significant increase in knowledge was for the processes in riparian areas. Ninety-five percent of the participants increased their knowledge by at least one level, 35 percent increased their level of knowledge by three to four levels, and 4 percent by five to six levels.

The other two questions were simple and straightforward: What were the strengths of the workshop? What could have been improved? Most participants responded that one of the strengths of the workshops was the quality of the presenters and the presentations. The presenters had diverse backgrounds and were interactive and open to answering questions. Many participants thought the workshops could have been improved if more local examples were presented, and this will be a focus in the future. The premise for this first set of workshops was to provide general information about riparian areas of Arizona. Another improvement that many participants would have liked would have been to tie in more practical applications, and that will also be a focus of future workshops.

The numbers and backgrounds of the participants were documented to assess the diversity of the public participating in the workshops. This provides insight into the extent of public involvement and interest in riparian areas. There were 186 participants in the seven workshops—a very encouraging number—indicating significant interest. The attendance for each workshop varied widely, ranging from only 9 to a maximum of 59 participants.

Overall, in every workshop the audience was very diverse. Workshop participants included agency employees (e.g. Bureau of Land Management, Forest Service, Natural Resource Conservation Service, Arizona State Parks, Arizona Game and Fish), professionals who deal with riparian areas (e.g. ranchers, miners), nongovernment organization employees (The Nature Conservancy), watershed partnerships, Master Watershed Stewards (trained volunteers in watershed management), and the members of the public with a general interest in riparian areas. The great diversity of the audience further increases our belief that many groups have a vested interest in riparian areas, and one success of the program was to bring these different groups together in one room.

An important first step in successfully maintaining and restoring riparian areas is to have all the different parties interested in riparian areas start communicating with each other. Most groups and individuals interested in riparian areas typically want the same thing—to have healthy and functional riparian areas. Riparian areas comprise a very small percentage of Arizona's landscape, and with the projected increases in population their importance and use and potential conflicts between user groups will surely increase over time. The best way to succeed in maintaining riparian areas and to meet public expectations for riparian areas is to enhance communication among the groups that use them or are interested in them. One significant group missing from the workshops was policy makers. Participants suggested that policy makers must be involved to maintain and restore riparian areas.

Another success of the workshops was to increase the public's awareness of available human resources (e.g. scientists, extension specialists, county directors/agents) who can address riparian area issues. These people can be very useful in the

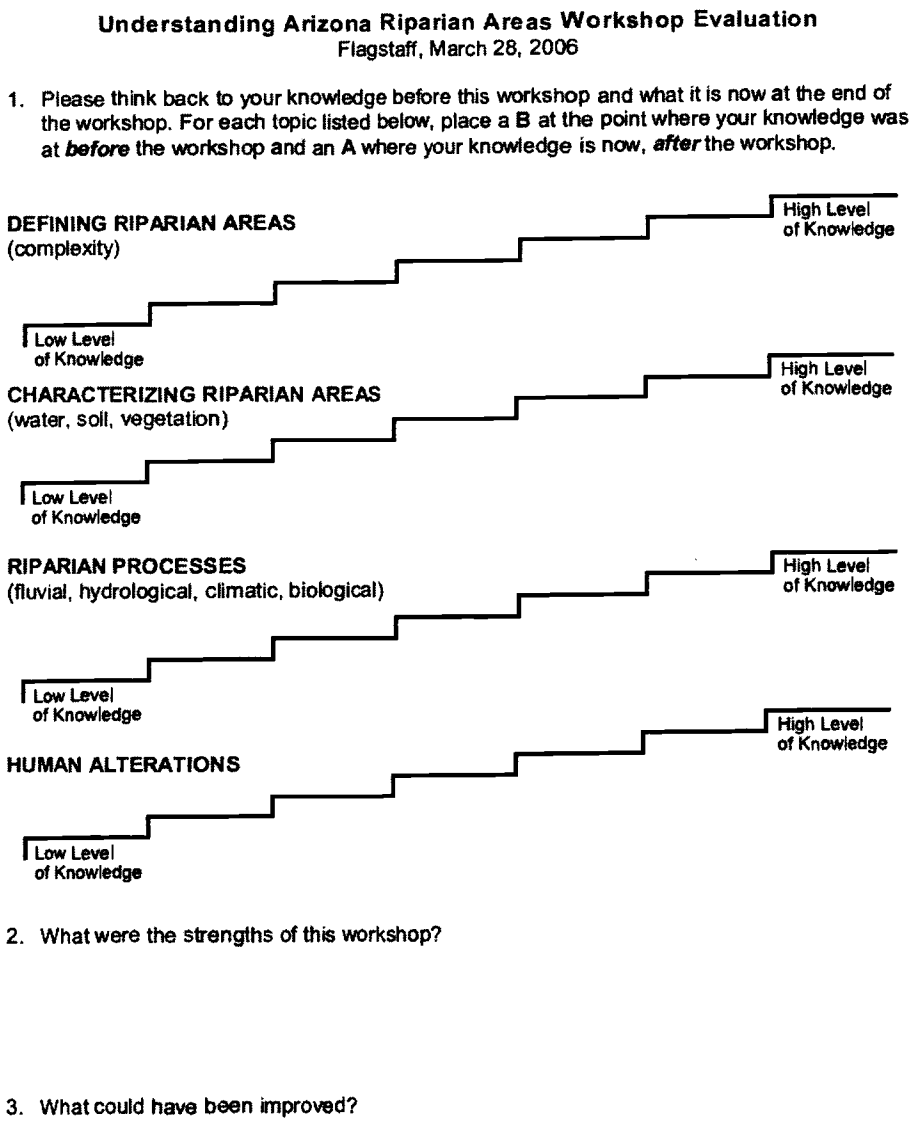

Figure 1. The evaluation form used to measure the success of the workshop.

future when riparian area issues arise for both participants and non-participants.

The workshops concluded with a discussion session. Participants were asked to answer key questions in order to identify future educational and research needs for riparian areas; these needs could be at the county or state level. This was a very important part of the workshops, as participants had the opportunity to express their personal opinions. Interacting with the audience is essential for a successful outreach program because it increases participant ownership in the workshop. In addition, the mission of cooperative extension is to provide educational programming to meet the public's needs. The needs assessment information for the first set of workshops will provide the basis for a second set of workshops to be conducted in the future.

It is important to point out that although some educational and research needs overlapped between counties, there were also educational and research needs specific to each county. The following summary primarily includes the overlapping educational and research needs based on participant responses from all counties. The major educational needs were these:

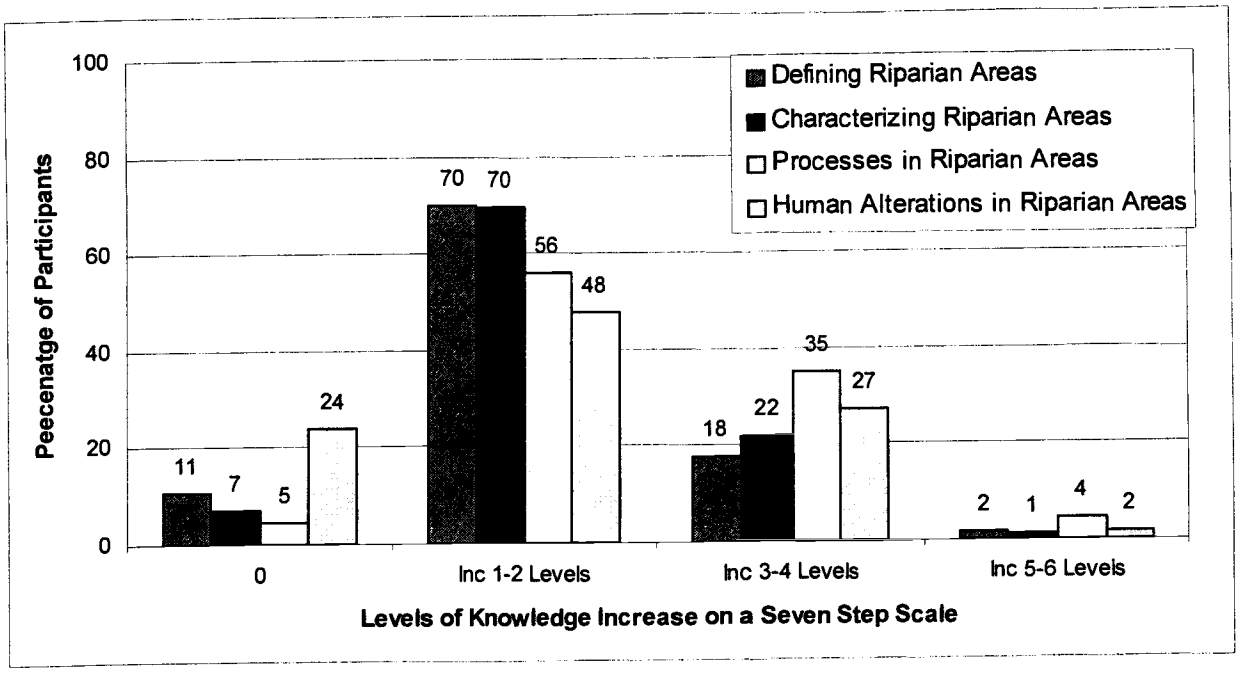

Figure 2. The percentage of participants who increased their knowledge at various levels by participating in the riparian workshops. The overall average was computed by the average of each county.

1. Develop a management session to discuss how to protect/restore riparian areas. Best management practices should be discussed and tied in with practical applications. The best management practices should address minimizing impacts from urbanization and recreation.

2. Explain proper monitoring techniques and practices for riparian areas.

3. Have workshops with riparian case studies (what has worked and what hasn't) from Arizona. These workshops should provide examples with tested practices. Provide more information on research and restoration projects and how people can get involved in restoration efforts.

4. Provide a venue or forum for facilitation and communication between groups. Specifically, provide a plan to help the various groups that have a vested interest in riparian areas to work together.

5. Provide a course for plant identification of obligate riparian species.

6. Include information on riparian areas in K-12 education.

7. Make the message on riparian issues easier to understand for the general public.

8. Provide more educational resource tools for Native American counties.

Responses to the needs assessment from the seven workshops will start to be addressed during the second set of workshops, which will focus on more local riparian issues and be more specific to each county. In addition, field trips will be part of the workshops because being on the ground can provide valuable insight. The major research needs based on the seven workshops were the following:

1. Develop a tool-kit for riparian systems, to include for example a monitoring protocol for the state of Arizona and methods for identifying the characteristics of high-quality riparian areas that should be preserved.

2. Determine what the desired and best potential conditions of riparian areas are.

3. Further research and evaluate the functionality of riparian exclosures and their effects on wildlife.

4. Study how watershed-scale management activities and disturbances impact riparian areas, and investigate the interconnections between the total area of the watershed and their riparian areas. Try to model the interconnections between riparian areas and watersheds.

5. Conduct more economics studies, for example on the cost/benefits of restoration projects, the

economics of riparian tourism, and the monetary value of riparian areas.

6. Explore methods to manage/mitigate major riparian invasive species.

7. Continue research for better riparian area classification (ecological sites) and identification. Enhance current mapping of the riparian areas of Arizona.

8. Study the impacts of using reclaimed water on riparian areas.

9. Increase riparian research projects in Native American counties.

10. Conduct more research in riparian areas that are being urbanized.

11. Conduct more studies on climate impacts (e.g. climate change, drought) on riparian areas.

EDUCATIONAL PUBLICATION

The educational publication "Understanding Arizona's Riparian Areas" was a supplemental resource for all participants of the workshops. The publication provides participants with a resource they can use in the future. The publication has seven chapters based on the seven topics of the presentations. The presenters of the specific topics in the workshops also wrote their specific chapters. The publication's total length is a little more than 100 pages. Currently, it has been submitted for review to the University of Arizona Cooperative Extension publications.

This educational publication will provide a great resource for the public interested in the riparian areas of Arizona. In the written evaluations many wrote that this publication was one of the strengths of these workshops. In addition, we have had many inquiries about the availability of the publication for purchase and for use as an educational resource. This publication will also help increase knowledge and awareness of riparian areas for the general public—our main objective.

EDUCATIONAL WEB MODULE

A Web-based educational module has been developed that draws on the materials and resources used in the educational workshops and the educational publication. As with the workshops and the publication, the Web module has seven chapters. The general idea is to use multi-media Web applications so learners will be presented with successive steps that introduce them to academic and practical information about riparian areas. Self-paced exercises will give learners practice with the concepts, and graphics and photographs will illustrate key points.

Early versions of the module were reviewed and evaluated by riparian experts and county agents and directors. The final version can be accessed at http://ag.arizona.edu/extension/riparian/. Access is free. The numbers of visitors to the Web site are continually monitored, and there is an online feedback form for visitor comments and evaluation. The completion of the Web module will be announced through various Cooperative Extension communication venues, and workshop participants who signed up to be informed about its completion will receive an email with the link. Almost all participants with Internet access, from all workshops, signed up to receive the link. This Web module serves as a resource for members of the public who were unable to participate in the workshop, as well as future professionals working in riparian areas. The Web module will have a long-term impact on the degree of knowledge and awareness about Arizona riparian areas. Finally, the goal is to continually update this Web module, which will include adding a section that illustrates successful case studies in riparian management.

CONCLUSIONS

Education is a powerful tool that should be utilized to its maximum potential. One of the missions of the University of Arizona Cooperative Extension and the School of Natural Resources is to provide information for the general public on key issues concerning natural resources—riparian areas are one such very important natural resource. Scientifically sound information was provided in three forms (workshops, publication, and Web module) that could be understood by most of the general public. The seven workshops significantly increased awareness and knowledge of riparian area issues and concepts (Figure 1) while the publication and Web module will provide resources about Arizona's riparian areas over the long term. Specifically, through the written evaluations (Figure 2) from the participants who attended the workshops, there was strong evidence that these workshops were successful at increasing knowledge levels. In addition, communication between the various groups with an interest in riparian areas has been achieved through the workshops. Finally, through the needs assessment discussion session of the workshops we have a better understanding of which issues future educational programs on riparian areas should address and the riparian research topics of interest to the public.

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INTERNATIONAL ARID LANDS CONSORTIUM'S CONTRIBUTIONS TO BETTER MANAGEMENT OF WATER RESOURCES IN ARIZONA AND THE SOUTHWESTERN UNITED STATES

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The International Arid Lands Consortium (IALC) was established in 1990 to promote research, education, and training activities related to the development, management, and reclamation of arid and semiarid lands in the United States, the Middle East, and elsewhere in the world. The IALC supports ecological sustainability and environmentally sound use of these lands by funding research, development, and demonstration projects related to these themes. Results from these scientific and technical efforts enhance management of arid and semiarid ecosystems for sustainable use within the framework of maintaining the integrity of the ecological processes involved. Among the areas receiving IALC attention are the development and conservation of soil and water resources, land use and reclamation, processes enhancing the management of ecological systems, and inventorying and measurement techniques and monitoring. Some of the contributions of the IALC to better stewardship of soil and water resources in Arizona and more generally the southwestern United States are summarized in this paper. A more comprehensive report on the accomplishments and contributions of the IALC to arid and semiarid land stewardship in its initial 10 years of existence can be found in Ffolliott et al. (2001).

GROUND WATER QUALITY AND NITROGEN FERTILIZERS

There is increasing concern in the southwestern United States about the possible contamination of ground water resources from nitrogen (nitrate-nitrogen) fertilizers applied to agricultural lands. The often excessive amounts of nitrogen fertilizer that agriculturists apply to shallow-rooted crops have resulted in the greatest contamination. Therefore, the IALC supported a project to demonstrate the use of a known chloride-tracer technology to improve nitrogen fertilization efficiency (Al-Jamal et al. 1998). Samples were taken at each of the participating farms in southern New Mexico to obtain baseline data on nitrogen-to-chloride ratios and efficiencies of nitrogen fertilizer applications. Samples obtained after adding a chloride tracer to the water were analyzed and compared to the baseline data. Using this knowledge, producers were able to make adjustments in the scheduling of nitrogen applications, which has resulted in improved ground water quality beneath their agricultural fields.

MITIGATING SOIL SEALING

Sealing of soil surfaces is a major concern in arid and semiarid environments. Sealing reduces infiltration of water and inhibits the emergence and survival of planted seedlings. One way to mitigate this sealing is to maintain a wet soil surface by frequent irrigation, but this approach is expensive and wasteful. Another way to improve soil surface structure and aggregate stability is by adding soil conditioners such as polyacrylamides (PAMs) to the soil surface. An IALC-sponsored investigation in Texas revealed that PAMs reduce the strength of soil-sealing crust, improve infiltration, and decrease the wind erodibility of soils with high sand and low silt contents (Gardiner and Carr 1998; Gardiner et al. 1998, 1999). Repeated applications of PAMs improve the persistence of these effects, although the emergence and survival of shallow-seeded plants does not appear to be consistently improved by PAMs or combinations of PAMs and gypsum. The interactions of polyacrylamides with soil characteristics, infiltration

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rates, seedling emergence, and other factors need further investigation.

USING WASTEWATER TO GROW TREES FOR PROFIT

The improper treatment and disposal of human waste affects many communities in arid and semi-arid lands by causing environmental degradation and declining public health. An IALC demonstration project served to increase awareness about environmentally sound and economically feasible wastewater treatment and disposal. Specialists in water and soil management, small-business development, and community planning from the southwestern United States and northwestern Mexico have collaborated in applying treated wastewater to landscapes unsuited for agriculture production to grow short-rotation pulpwood trees for sale in local markets. This low-cost approach safely recycles sludge and wastewater from small- to medium-sized communities along the Rio Grande on both sides of the border. This project serves as a useful model for combining wastewater treatment and disposal with economic development of other local communities.

WATER USE BY EMORY OAK

Other than precipitation, water used for transpiration is the largest component in the water budget of Emory oak stands (Ffolliott 2004). To learn more about how land-use activities affect transpiration by Emory oak—a widely distributed drought-deciduous species in the southwestern United States—the IALC supported studies to increase people's understanding of the changes in the relative proportions of water consumed by harvesting the trees for wood products and their subsequent regeneration. Transpiration rates were estimated by the heat-pulse method (Swanson 1994) in these investigations. One of the more important findings was that stump-sprouts growing from rootstocks of harvested oak trees can use up to 80 percent of the annual precipitation in the transpiration process in comparison to about 45 percent of the annual precipitation used by mature trees 60 years and older in unharvested stands (Ffolliott et al. 2003). Even though the transpiration rate of a single stump-sprout is significantly less than that of a mature tree, the greater transpiration rates in harvested stands is attributed to the large number of actively growing stump-sprouts. There is thus less water available to recharge ground water aquifers, produce streamflow, and help other plants to grow when stump-sprouts dominate a site following the harvesting of Emory oak trees. This research provides a basis for managing post-harvest oak stands to optimize water conservation and firewood production, and through the results of companion studies, to benefit other resources in these fragile woodlands (Shipek et al. 2004).

CLIMATE CHANGE, ALLOMETRY, TREE HYDRAULICS

Managers of forests and woodlands are increasingly concerned about the effects that the expected increases in air temperature and atmospheric vapor-pressure deficits in the twenty-first century might have on the growth of trees. Because the most relevant allometric component controlling water transport in trees is the ratio of biomass allocated to photosynthetic tissue (leaves) relative to water-conducting tissue (sapwood), IALC researchers used published values to test a theoretical model predicting that ponderosa pine trees decrease their investments in leaves relative to sapwood as air temperature and atmospheric vapor-pressure deficits increase (DeLucia 1999). They found that desert-growing ponderosa pine trees in a desert-to-montane gradient of Nevada are likely to have higher rates of water-transport per unit of sapwood than montane-growing ponderosa pine trees because of larger-diameter tracheids in the sapwood (Maherali and DeLucia 2000a, 2000b). Inferences drawn from this study should help managers to select ecologically adapted genotypes of ponderosa pine for wood production or other purposes in warm and dry climates that are similar to those of the southwestern United States.

WATER CONSERVATION BY DRIP IRRIGATION

Traditional methods of irrigating agricultural crops in the southwestern United States have largely been through inefficient flood and sprinkler systems. However, effective irrigation practices and water conservation measures are necessary for irrigated agriculture to remain profitable and economically acceptable in the region. Recent innovations in efficient drip-irrigation technology have enhanced its usefulness (Powell and Wright 1993; Camp et al. 2000). A drip-irrigation system installed at the Agricultural Science Center of New Mexico State University illustrates the use of subsurface drip-irrigation methods for growing alfalfa. This IALC project demonstrates the water savings and economic benefits from applying this system rather than flood or sprinkler irrigation

methods. The reduction in water used for profitable agricultural pursuits helps to restore streamflows and improve available ground water.

WATER HARVESTING AND TREATED WASTEWATER FOR IRRIGATION

Many methods continue to be used to develop water supplies for people living in arid and semiarid regions. Irrigation with saline water, use of treated wastewater, and water harvesting are examples. Investigators in an IALC research effort evaluated the possibilities of successfully growing trees (velvet ash, black willow, Fremont cottonwood, eucalyptus, and Modell pine) near Tucson, Arizona, by irrigating them with combinations of potable water, treated wastewater, and harvested rainwater (Karpiscak and Gottfried 1998, 2000). They found greater survival and initial growth in some tree species when irrigated with treated wastewater combined with harvested rainwater in comparison to irrigating with potable water. However, long-term monitoring of the growth and survival of the trees is necessary before basing management decisions on applying this technology. Whether trees take up harmful constituents in the treated wastewater or whether a soil irrigated with the effluent is adversely impacted also remains to be determined.

URBAN EROSION CONTROL AND STORM WATER HARVESTING

Excessive soil erosion, water allocation, pollution of surface water and ground water, and wastewater collection and treatment are major concerns to the people of municipalities along the southwestern United States–Mexico border. The "twin cities" of Nogales (Arizona) and Nogales (Sonora) share the hydrologic and hydraulic characteristics of a common watershed. The steep hills surrounding Nogales (Sonora) are largely denuded of vegetation and are thus readily eroded during heavy rainfall. Drainages that are normally dry become runoff channels and conveyors of sediment-laden flows that leave deposits on roadways and threaten homes and other buildings. These deposits are rapidly converted to atmospheric dust, resulting in the noncompliance of Nogales (Arizona) with U.S. clean-air standards for particulate matter. The IALC is supporting a demonstration project that illustrates how excessive soil erosion can be controlled structurally by planting native vegetation and using water-harvesting techniques that augment the scarce water supplies.

VEGETATION DYNAMICS AND LANDSCAPE VULNERABILITY TO WILDFIRE

Prolonged drought, high-severity wildfire, and high-intensity rainfall events have a devastating impact on the sustainable use of natural resources throughout the dryland regions of the world. In addressing this critical issue, IALC researchers are integrating remotely sensed seasonal and geospatial vegetation and climatic data and information from soil-erosion plots to assess land degradation and potential recovery after wildfire events. Sites in Arizona, Spain, and Israel are the focus of this assessment; the Arizona site is situated in the historic Rodeo-Chediski wildfire area. The landscape degradation assessments are evaluated in terms of vegetation recovery after wildfire events (Ffolliott and Neary 2003). When fully developed and tested, the predictive model will allow planners and managers to generate representative maps of land degradation and risk of post-fire erosion on watersheds at regional scales, making it possible to focus efforts where risks are the greatest. Identified sensitive or vulnerable sites should have priority in management programs for fire prevention and, when necessary, post-fire mitigation. Furthermore, decision makers will be able to assess the ability of landscapes to support various land uses.

MONITORING IN REMOTE AREAS

Sampling of large rainfall and runoff events and other outlier events is difficult in the southwestern United States and other arid and semiarid regions because of the variable occurrence of these events. Encountering extreme or outlier events on remote and often sparsely monitored watersheds is more likely than on a single instrumented watershed, a situation that compounds this problem (Renard 1970; Singh and Woolhiser 1976; Morin and Sharon 1993). To address this situation, IALC-sponsored researchers explored the feasibility of identifying and analyzing data sets for large rainfall and runoff events occurring on remote and sparsely monitored watersheds to become proxies for information obtained from instrumented watersheds to reduce the time and cost of obtaining long-term data from a single instrumented watershed that might not represent the larger remote area.

Studies conducted on the Walnut Gulch Experimental Watershed in southeastern Arizona have provided insight about how to estimate the character of these outlier events on watersheds without instrumentation. Peak stormflows from

isolated watersheds can be estimated from knowledge of surface water profiles indicated by high-water marks and post-flow stream channel geometries. The level of uncertainty associated with these indirect estimates of peak stormflow was also determined in this study. The researchers concluded that these methodologies could be expanded to improve estimates of hydrologic processes on lands with little or no ground-based monitoring.

DISSEMINATION OF WATERSHED MANAGEMENT INFORMATION

Watershed managers throughout the world are formulating and implementing actions that result in the manipulation of natural and human resources to satisfy specific goals and objectives. Watershed management in the southwestern United States is particularly challenging because water supplies and associated resource productivity levels are limited. In addressing this challenge, watershed management research has led to a better understanding of the hydrology, ecology, and land-use potentials of the region's watershed landscapes (Baker 1999). While this research has helped establish management guidelines to meet the needs of the growing population, the findings obtained are not necessarily widely known or readily accessible. An IALC demonstration project increases the accessibility of these findings to a broader audience, and in doing so helps people to improve watershed management decisions and efficiencies by involving a greater number of stakeholders in the decision-making process. A main part of this effort involved bringing the research information to the interested public through the World Wide Web. Thus, "Watershed Management in the Southwest" (http://www.ag.arizona.edu/OALS/watershed) includes a variety of topics on watershed management practices, displays of accessible baseline data sets, and an interactive learning package on watershed management practices (Baker and Young 2000; Haseltine et al. 2002). A recent phase of this effort involves a coupling of GIS applications to allow users to search, chart or graph, and compare precipitation, streamflow, vegetation, and other watershed-based resource characteristics through a dynamic interface on this useful website.

SURVIVORS IN THE SAND

The IALC supported the development of a video, called *Survivors in the Sand*, prepared by media specialists at New Mexico State University that has increased people's awareness of watershed-based natural resources and their management issues. Conservation, sustainable use, and management of arid and semiarid lands were documented in this 1-hour video through on-site interviews and film archives from the southwestern United States and other arid regions of the world. The conservation of water resources, land reclamation treatments, and sustaining endangered and threatened species are highlighted in the video. There has been widespread airing of *Survivors in the Sand* by public and private television and educational institutions. It has won awards at the New York International Film and Columbus International Film and Video Festivals. The video has generated, and continues to generate, awareness of, interest in, and support for better management of land, water, and other natural resources on arid and semiarid lands.

SUMMARY

Scientific and technical efforts of the IALC to learn more about the ecological sustainability and development of arid and semiarid landscapes such as those represented by the southwestern United States are continuing. Results from these efforts enhance the management of arid and semiarid ecosystems for sustainable use of their natural resources within the framework of maintaining the integrity of the ecological processes involved. Enhancing the level of knowledge related to the soil and water resources in these fragile ecosystems is paramount in the efforts. The importance that the IALC continues to place on water resources in its solicitation of research, development, and demonstration projects has been reinforced by focusing this year's requests for proposals on broadly based water-related themes.

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