CONTRIBUTIONS OF SNOWMELT TO STREAMFLOW IN SOUTHEASTERN ARIZONA: A CASE STUDY FROM THE SANTA CATALINA MOUNTAINS

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The Sky Islands or Madrean Archipelago region of the southwestern United States and northwestern Mexico is recognized for its biological diversity and natural beauty. These attributes are accentuated by the landscape with its network of mountain ranges or "islands" separated by valleys of desert scrub or grassland vegetation. The population of people in the Desert Southwest has grown tremendously since World War II and continues to grow as people as drawn to the region because of its mild climate and economic opportunities. One report indicates that more than 300,000 people moved to southeastern Arizona from 1994 to 2004 (Gottfried and Hodges 2005). Water is a critical resource if the existing population growth is to be sustained. Snowmelt from high elevation headwaters is a primary source of runoff for the major rivers of the Southwest. Approximately 3.0 to 5.1 million ac-ft of water can be stored in the mountain snowpacks of Arizona and New Mexico before spring snowmelt (Ffolliott et al. 1989). However, snowpack conditions in the forests of the Southwest are variable with years of high or low accumulations being common. Southwestern snowpacks, unlike those in more northern regions, melt intermittently throughout the winter and, at intermediate elevations between 7,000 and 7,500 ft, can appear and disappear during a winter (Gottfried et al. 2002). Precipitation from warm winter storms at these elevations can fall as rain, resulting in rapid snowpack ablation and accelerated runoff. Snowmelt runoff from the Sky Islands is locally important for wildlife, riparian vegetation, livestock, isolated residences, and recreation but has a low potential as a regional water source (Ffolliott et al. 1996). The snowpacks cover relatively small forested areas of the mountains and channel transmission losses of water would be large considering the distances between the forests and the valleys.

SNOW SURVEYS

The need to monitor runoff from the mountain drainages resulted in the establishment of stream gauging stations on several major drainages by the U. S. Geological Survey (USGS) and other governmental agencies. The USDA Soil Conservation Service (SCS) (now the Natural Resources Conservation Service (NRCS)) established snow courses and later electronic snow telemetry stations (SNOTEL) throughout the high country of the West to monitor changes in snowpack conditions throughout the winter to help predict streamflow in the major river systems. However, the snow courses do not reflect snow conditions in their locations and immediately adjacent areas because they are generally established on sites where snowpacks will accumulate, and are more representative of snow conditions at higher elevations (Gottfried and Ffolliott 1981, Gottfried et al. 1998). Rather, they serve as an index of snowpack dynamics within a mountain range. Snow is generally measured six times during a winter from January 15 to April 1 to determine peak accumulations that can occur on any of those dates depending on storm activities and temperatures. The surveys are not conducted on the exact date but as close to it as possible.

Snow surveys began in Arizona and New Mexico in 1937 to forecast streamflow in the Salt and San Francisco Rivers (Jones 1981). At one time, there were 75 snow courses in Arizona and adjacent New Mexico but many have been discontinued and data collections consolidated at the SNOTEL installations. The SCS summarized snow measurements for Arizona and adjacent portions of New Mexico and produced annual summaries. The SCS established two snow courses in the Madrean Archipelago as part of this effort and both were in the Santa Catalina Mountains north of Tucson. The two courses, Rose Canyon and Bear Wallow, were monitored from 1948 through 1983 (Jones 1981). Two aerial snow markers also were located at about 10,000 ft in elevation in the Pinaleño Mountains south of Safford but these were only measured for about 10 years.

EARLIER STUDIES

Scientists from the U.S. Forest Service, Rocky Mountain Research Station and the School of Natural Resources and the Environment of the University of Arizona have examined the relationships between peak snowpack accumulations measured at NRCS stations and streamflow quantities and peak mean daily runoff from gauged headwater watersheds. The watersheds were monitored by the U.S. Forest Service, Rocky Mountain Forest and Range Experiment Station (now the Rocky Mountain Research Station) to determine the effects of experimental forest management treatments on hydrologic and biological resources. Significant regression relationships have been determined between peak snowpack accumulation and snowmelt runoff

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characteristics for the Workman Creek watersheds in the Sierra Ancha Mountains, north of Globe, and for Willow Creek East Fork in the White Mountains of eastern Arizona (Gottfried et al. 2002). The Workman Creek snow course is located at 6,900 ft and represents a zone where the snowpack characteristics usually fluctuate throughout the winter because of intermittent melting between storms and occasional rain-on-snow events. The Hannagan Meadows snow course at 9,090 ft was related to streamflow at Willow Creek. This higher elevation area represents a zone which experiences less intermittent melting and where rain-on-snow events are uncommon.

Relatively little is known about snowpack dynamics and the contributions of snowmelt to streamflow in the relatively isolated Sky Islands of southeastern Arizona. Some general descriptive data from the two Santa Catalina snow courses were summarized by Ffolliott et al. 1996). Gottfried et al. (1998) studied accumulations and ablation on these two snow courses and within a 40-acre forested experimental watershed near the top of Mount Lemmon during the record snowfall season of 1967-1968. The watershed, which had been established by the University of Arizona, contained 70 survey points. Heavy snowfalls can occur in the higher Sky Island Mountains (table 1). Approximately 14.7 inches of water equivalent were measured at Bear Wallow on January 15, 1968 (Jones 1981), the first survey following the large storm in December 1967.

Historical data sets obtained on SCS/NRCS snow courses on the Santa Catalina Mountains and streamflow measurement at the Lower Sabino Creek gauge, maintained by the USGS, are used as a basis to make a comparison between the two and, in doing so, determine whether snowpacks contribute significantly to streamflow regimes from the mountain. A comparison of these findings to the results from similar investigations in other areas of Arizona where more extensive snowpacks occur is also presented.

STUDY SITES

Sabino Creek is one of the major drainages on the south side of the Santa Catalina Mountains. The watershed for the ephemeral stream covers 22,720 acres and extends from 2,720 ft at the gauging station to 9,200 ft at the top of Mount Lemmon. The mean watershed elevation is 6,300 ft and the main channel has a slope of 482 ft/ mile (Pope and others 1998). The lower reaches of Sabino Creek contain a paved road and are heavily used by recreationists from the Tucson Metropolitan Area. The Coronado National Forest GIS data base, which includes areas below the gauging station, indicates that the watershed contains 29,599 acres (Austin, T., personal communications, 2004) that

TABLE 1

AVERAGE SNOW WATER EQUIVALENTS (SWE) FOR FOUR ARIZONA STATIONS

Snow Course	Elevation (ft)	Location	Snow Water Equivalent (in)	Snow Depth (in)
Workman Creek	6,900	Tonto N. F.	18.4	50
Mingus Mountain	7,100	Prescott N. F.	8.6	24
Rose Canyon	7,300	Coronado N. F.	11.6	29
Fort Valley	7,350	Coconino N. F.	6.1	24
Happy Jack	7,630	Coconino N. F.	8.7	30
Coronado Trail	8,000	Apache-Sitgreaves	11.6	31
Bear Wallow	8,100	Coronado N. F.	14.7	38
Nutrioso	8,500	Apache-Sitgreaves	8.6	25
Hannagan Meadow	9,090	Apache-Sitgreaves	16.0	49
Fort Apache	9,160	Apache-Sitgreaves	11.6	36

are divided into five major vegetation types: southwest desert scrub (9 percent of the watershed), deciduous riparian (4 percent), broadleaf woodland (47 percent), ponderosa pine (transition) forest (36 percent) and mixed conifer forests (4 percent). The ecology of the south side of the Santa Catalina Mountains has been described by Whittaker and Niering (1964), Niering and Lowe (1984), and others. Geologically, the south side of these mountains consist of almost vertical bedrock outcrops and steep talus slopes that are covered by thin colluviums, about 20 inches deep (Magirl et al. 2007).

STREAMFLOW INSTALLATIONS

The USGS gauge (USGS 0948400) contains a water-level recorder and concrete control (Pope et al. 1998). The initial hydrologic record extends from 1932 to September 1974. A crest-stage gage was used from 1974 to August 1981 when a recording stage recorder was reinstalled and the continuous record extended until today. The gaging station was moved downstream in 1974. The streamflow data are from the USGS web site: http://nwis.waterdata.usgs.gov. Months with missing or questionable data for more than a minimum of days are not reported and are not used in statistical calculations. Only annual peaks are listed for 1974 through 1984, and some data for 1974 through 1988 have not been published. A review of monthly mean streamflow from July 1932 through January 2011 (figure 1) indicates that most runoff occurs between December and April when frontal storm from the Pacific cross Arizona producing snow at the higher elevations. March has the largest mean of monthly streamflows. Peak annual runoff occurred during the winter months in 44 percent of the years, with a maximum peak of 12,890 cfs occurring on January 8, 1993, and a median peak of 2013 cfs (Desilets et al. 2007). Approximately 56 percent of the annual precipitation occurs in the summer monsoon season but these storms generally produce little runoff because of high evapotranspiration and low soil water. However, high-intensity convectional thunderstorms storms have produced 64 percent of the annual peaks measured at the Sabino Creek gauge. The highest peak flow for an individual event was 15,700 cfs that occurred on July 31, 2006 after three days of heavy rain (Magirl et al. 2007).

A gauging station was established to measure flows in the upper reaches of Sabino Creek near Mount Lemmon. The installation measured flow from a 2,042-acre watershed with a mean elevation of 7,900 ft, from May 1951 through March 1959. Limited information has been reported for later dates. The historic peak flow on record was 380 cfs on September 13, 1966 although a larger peak might have occurred on September 5, 1970 during the Labor Day Storm but the discharge has not been calculated.

The greatest monthly mean streamflow on record occurred in January 1952 when 15.6 cfs were measured. The next highest was in March 1954 with 14.0 cfs. The greatest overall mean of monthly streamflows at the upper station occurred during snowmelt in March and April. A comparison with the Lower Sabino gauge records for the same period indicated that the upper watershed produced about 25 and 36 percent of the flow measured

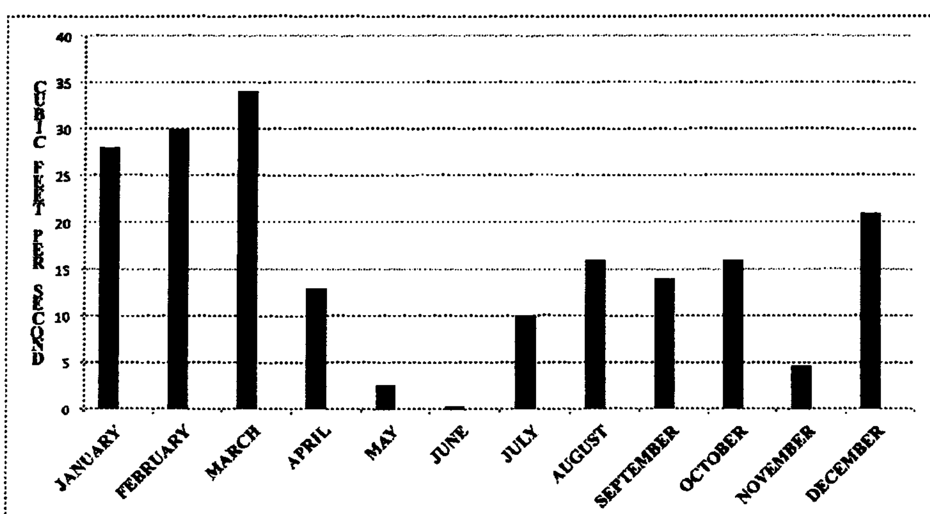

Figure 1. Mean monthly streamflow at the Lower Sabino Canyon Gauge 1932-2011 from US Geological Survey records.

for the entire watershed in April and May. In the seven-year-period from January 1952 through June 1958, the upper gauge measured an average of 16 percent of the amount measured at the lower gauge. Transmission losses between the two gages would affect the flow percentages. The means for June, for example, indicated more runoff from the upper area than was measured at the lower gauge.

SNOW COURSES

The Rose Canyon and Bear Wallow snow courses were located within the Sabino Creek watershed on the south side of the Santa Catalina Mountains. Rose Canyon is located at 7,300 ft in elevation and Bear Wallow is at 8,100 ft. The record covers 36 years from 1948 through 1983. The typical snow course contains between five and ten measuring points; Bear Wallow contains eight points and Rose Canyon contains seven points. Measurements made with a federal snow tube include snow depth and water equivalent that are used to calculate snowpack density, an indicator degree of ablation. Both areas originally were surrounded by large, old-growth ponderosa pine (Pinus ponderosa) trees. Bear Wallow also contained other species associated with southwestern mixed conifer forests such as Douglas-fir (Pseudotsuga menziesii), southwestern white pine (P. strobiformis), and white fir (Abies concolor). Overstory stand densities surrounding the snow courses averaged 100 ft2/ac of basal area at Bear Wallow and about 50 ft2/ac of basal area at Rose Canyon (Ffolliott et al. 1996). The areas surrounding the snow courses were burned in the Aspen Fire in 2003 that burned 81 percent of the mixed conifer forest and 99 percent of the ponderosa pine forest in Sabino Canyon (Austin, T., personal communications, 2004).

SNOW COURSE MEASUREMENTS AND SABINO CREEK STREAMFLOW

Average snow water equivalents fluctuate throughout the winter with peaks occurring on February 15 (figure 2). On that date, the Bear Wallow snowpack had about 4 in of water and Rose Canyon had 2.5 in of water. The Bear Wallow records show a secondary but smaller peak on March 15 while Rose Canyon snowpack record indicates a general decline because of higher temperatures and melt rates. On an average, 70 percent of the seasonal peak accumulations of snow water content at Rose Canyon were measured during one of the first three visits compared to 59 percent at Bear Wallow. Annual peak accumulations occurred on 22 percent of the March 15 visits to Bear Wallow.

The Upper Sabino Canyon gage, while operating, recorded streamflow from these higher elevations. A significant linear regression indicated that data from the Upper Station could predict winter streamflow at the Lower Station with a coefficient of determination of 0.80. A regression was also developed between the snow water equivalent measurements at Rose Canyon and streamflow volumes at the Lower Sabino gauge for the winter months. The regression had a coefficient of determination of 0.42. However, the coefficient of determination changed ($r2 = 0.63$) when data from the winter of 1958 were not included. Records and personal observations indicate that most of the precipitation during that year fell as rain and the snowpack had a minimal impact on runoff. Mean runoff at the upper station was relatively high in March and April 1958 with means of 9.9 and 9.7 cfs, respectively, possibly indicating rain at that elevation. A similar situation occurred at Workman Creek. The analyses of the relationships between

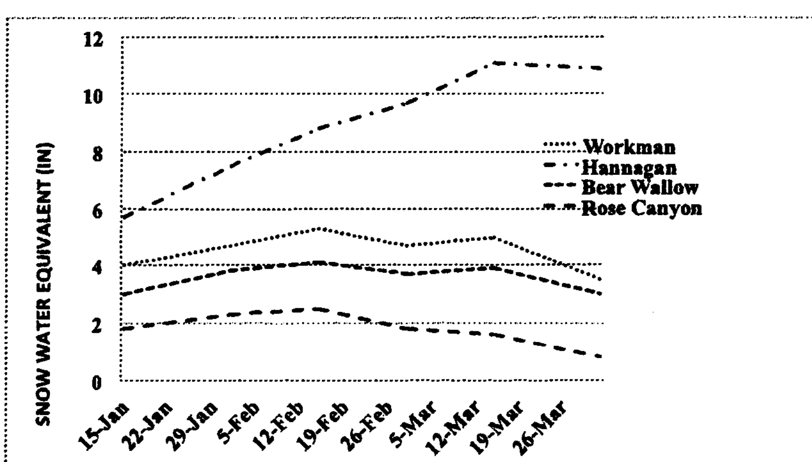

Figure 2. Average snow water equivalents for four Arizona snow courses.

snowmelt runoff and snowpack water equivalents also improved when 1954, a year of heavy winter rains, was not included (Gottfried et al. 2002). High streamflows were measured in the years with heavy rains when the snowpack contained minimum amounts of water. No snow was measured at Rose Canyon during 1972.

This relationship is apparent in comparing values for winter runoff as a percent of peak snow water equivalents at the Rose Canyon snow course (figure 3). The peak snow accumulation data in inches were converted to cubic feet assuming that measurements represented the 7,718-acre ponderosa pine belt. This value is an estimate because even the first snows do not cover the landscape evenly because of interception by tree and shrub crowns and wind action. Later in the winter, sites on south-facing slopes and around trees where melting has occurred would have less snow cover from a heavy storm than other areas. In addition, some of the water generated from the snowpack is lost in transmission and new water from the lower part of the watershed is added to streamflow. However, recognizing the limitations, there are 19 years when winter runoff (January through June) measured at the lower gauge was less than the potential water available in the snowpack. The influence of the 1958 rains is apparent when the gauge measured 1200 percent of the volume of water in the snowpack (figure 3).

COMPARISONS OF THE SANTA CATALINA SNOWPACK WITH OTHER ARIZONA SNOWPACKS

The higher elevation and relatively isolated mountains of Arizona that intercept winter storms have a history of high peak snowpack accumulations especially during large frontal storms. A comparison of snow depths and snowpack water equivalent data from 10 snow courses for a large storm in December 1967 showed that the highest accumulations occurred at Rose Canyon, Bear Wallow, and Workman Creek. Workman Creek, which is located at the eastern edge of the Tonto Basin, had the most precipitation. This location also has recorded the highest Arizona totals in the Labor Day Storm in 1970. Excluding Workman Creek, only Hannagan Meadow at 9,090 ft in the White Mountains had more snow water than the Bear Wallow site, while Rose Canyon was equivalent to the higher elevation Coronado Trail and Fort Apache sites.

The importance of elevation is apparent when reviewing snowpack water equivalent data from the two Santa Catalina snow courses and the 40-acre University of Arizona watershed on the top of Mount Lemmon. These data reflect snow melt and new snowfall between measurement dates. The watershed extends from 8,400 to 9,157 ft in elevation, and snow accumulation and melt were measured from January 15 through May 15. Most snow was attributed to the December 1967 storm (Gottfried et al. 1998). The watershed snowpack had 15.5 in of water equivalent and 52.5 in of depth on January 4, 1968. These measurements were greater than all stations shown in table 1, except Workman Creek and Hannagan Meadow. Little net snowmelt occurred until April 1; when the watershed had an average of 10.9 in of water on April 21, and more than 4 in of water on May 12. Rose Canyon was at peak accumulation on the first survey date. The snowpack remained relatively constant until February 15, then declined with a slight

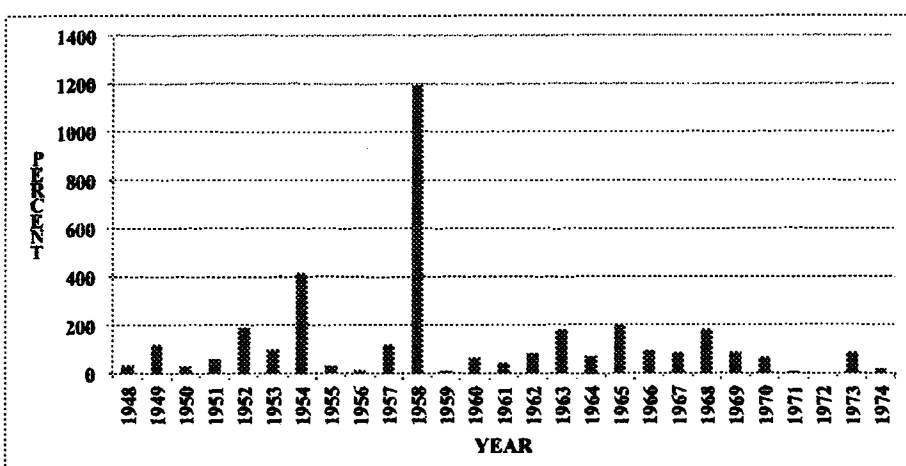

Figure 3. Winter runoff as a percent of estimated Rose Canyon peak snow water equivalents.

increase recorded in March, and was bare on April 1. Bear Wallow started at 14.7 in of water equivalent that continued to increase through February 1 and then slowly declined. It also recorded increased water during the March 15 visit. There were 10.8 inch recorded on April 1, the last visit of the season.

The average snowpack water equivalent measurements by that date also shows the snowpack dynamics throughout a season (figure 2). Each watershed has different lengths of record, for example, Workman Creek measurements began in 1952, the Santa Catalina measurements began in 1948, and Hannagan Meadow began in 1963. Workman Creek averages more snow than the Santa Catalina snow courses but follows the same general trends. Hannagan Meadow on the Colorado Plateau accumulates moisture throughout the season and does not show much melting by April.

CONCLUSIONS

Snowpacks develop annually in the higher mountains of the Madrean Province in southeastern Arizona. While this moisture might not greatly impact regional water supplies, it is important for recreation, local communities, and sustaining the important Madrean riparian, woodland, and forest ecosystems (Gottfried et al. 1998). Snowpack information is important for managers and individuals who need access into high elevation areas during winter months. Sabino Creek in the Santa Catalina Mountains was an important source of local water for the Tucson Valley and is now an important recreation area for southern Arizona. Consequently, the watershed has been gauged by the U.S. Geological Survey since 1932. Snowmelt produces a large amount of the winter streamflow, and high streamflow events can be detrimental to recreationists and recreational developments in the canyon. The Soil Conservation Service recognized the importance of the Mount Lemmon snowpack and established the Rose Canyon and Bear Wallow snow courses although they have since been decommissioned. This paper examined the relationship between the snow courses and streamflow volumes measured at the lower gauging station and at one near the top of Mount Lemmon. Significant statistical relationships were developed between peak snow water equivalents and streamflow volumes although the relationship is weaker when winter rains dominate the seasonal precipitation.

There are little data on snowpack characteristics and dynamics within these isolated mountain ranges. Documentation of the snowpack conditions on the Santa Catalina Mountain watershed confirmed many of the recognized relationships between snowpack dynamics and elevation. Measurements from the SCS snow courses at Rose Canyon and Bear Wallow provide an elevation gradient of snow data from above 7,000 ft in the lower ponderosa pine-oak forests, through the upper ponderosa pine forests to the mixed conifer forests. The one year of data from the University of Arizona watershed extends the elevation gradient to the top of Mount Lemmon. Since extreme wet and dry conditions are more common in the Southwest than average situations, knowledge of snowpack accumulations and especially, snowmelt dynamics in a wet year can be important for planning and conducting activities by land, wildlife, recreation, and water managers.

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