SNOWPACK DYNAMICS ON A SANTA CATALINA MOUNTAIN WATERSHED DURING A WET WINTER

Gerald J. Gottfried,[1] Peter F. Ffolliott,[2] and Malchus B. Baker, Jr.[1]

Most of the precipitation in the mountains of the Madrean Province of the southwestern United States and northern Mexico occurs as rain (Baker et al. 1995); however, snow is common at higher elevations. Measurable snowpacks occur annually in the higher mountain ranges, which extend to elevations of over 9000 ft in southeastern Arizona. A review of 36 years of USDA Soil Conservation Service, currently the Natural Resources Conservation Service, snow course records from the Santa Catalina Mountains, north of Tucson, shows that a snowpack was measured at some locations during every winter (Ffolliott et al. 1996). The largest measured snow accumulation in these mountains occurred in February 1966 when 19.6 inches of water equivalent were recorded at Bear Wallow at 8100 ft. However, snowpack conditions are variable throughout the Southwest, with years of high and low accumulations being more common than average years (Ffolliott et al. 1989). Most snowpacks go through cycles of melting and accumulation during a winter, and can disappear at intermediate elevations or drier sites, depending on the distribution of storms. Snowpacks in the Madrean Province may not represent a significant water supply potential (Ffolliott et al. 1996) because of their limited aerial extent and intermittent nature. Snowpack-generated streamflows also are reduced by high stream channel transmission losses, although some of this water contributes to groundwater recharge in the lower basins. However, snowpacks are important for snow-related recreational activities, as a source of water for mountain communities, and for the maintenance of riparian and high-elevation forest and woodland ecosystems. Managers should understand snow accumulation and melt characteristics when planning and conducting activities within stream channel systems and high-elevation areas.

There is limited information about snowpack dynamics on the mountain watersheds of the Madrean Province. Most snow information for the region was collected by the USDA Soil Conservation Service (SCS). The SCS, in cooperation with the USDA Forest Service, Coronado National Forest, established the Bear Wallow and Rose Canyon snow courses on the Santa Catalina Mountains during the winter of 1947–1948 and monitored them through the 1982–1983 winter season. Data from these two courses have been published (USDA Soil Conservation Service 1981) and summarized (Ffolliott et al. 1996).

The purpose of SCS snow surveys in the western United States is to provide an index of snowpack conditions to forecast snowmelt-runoff volumes. Snow courses do not necessarily reflect conditions on the immediate watershed because they generally are established on sites where a snowpack would occur, even in drier years. They tend to collect more snow than surrounding areas, and often reflect watershed snowpack conditions measured at higher elevations. Gottfried and Ffolliott (1981) studied several SCS snow courses in central and eastern Arizona and determined that they represented snow conditions found at an average (with standard error) of 363 ± 229 ft higher in elevation.

The School of Renewable Natural Resources, University of Arizona, instrumented a watershed on Mount Lemmon in the Santa Catalina Mountains in the late 1960s under a special use permit with the Coronado National Forest. One objective was to study forest hydrology at the watershed level. The area was monitored for approximately 4 years. The Mount Lemmon watershed provides an opportunity to study snowpack accumulation and ablation on a forested watershed during the unusually wet winter of 1967–1968. The objective of this paper is to describe and document snowpack dynamics associated with a wet winter within a southeastern Arizona mountain watershed. Results from the watershed are compared to SCS

[1]USDA Forest Service, Rocky Mountain Research Station, Flagstaff, Arizona
[2]School of Renewable Natural Resources, U. of Arizona, Tucson

snow course data from Bear Wallow and Rose Canyon, which are at lower elevations. Snowpack differences between north and south-facing slopes on the watershed also are compared.

Precipitation—Winter of 1967–1968

Precipitation during the winter of 1967–1968 was dominated by a pair of major storms that moved through Arizona from December 12 through December 20, producing significant moisture as rain and snow (U.S. Department of Commerce, Environmental Science Service Administration 1968a). Snow was reported at elevations as low as 1000 ft. The storm was cold, producing near record low temperatures. The Flagstaff airport reported 7.30 inches of water in 88 inches of snow, the Phoenix airport had 3.98 inches of rain, and the Tucson airport reported 3.44 inches. Crown King, in the Bradshaw Mountains southeast of Prescott, reported 16.95 inches of precipitation. The Palisades Ranger Station at 7945 ft in the Santa Catalina Mountains recorded about 8.40 inches of precipitation for the two storms. Although the storms produced over half of the winter precipitation in parts of Arizona, they only accounted for 40 percent of the 21.23 inches of precipitation recorded at Palisades from October 1967 through May 1968 (Sellers and Hill 1974). However, snow accumulations were often greater in the mountains of central and southeastern Arizona than at equal and some higher elevations on the Colorado Plateau. This is reflected by data from a sample of snow courses in central Arizona for January 15, 1968, when the first surveys were conducted (Table 1). Bear Wallow, with 14.7 inches, had more snow water equivalent than all other stations except Hannagan Meadows, which lies at 9090 ft in the White Mountains of eastern Arizona, and Workman Creek at 6900 ft in the Sierra Ancha Mountains, north of the Santa Catalina. Rose Canyon, at 7300 ft, with 11.6 inches had more snow water equivalent than most locations and was equal to the Coronado Trail (8000 ft) and Fort Apache (9160 ft) in the White Mountains.

Study Areas

The Mount Lemmon watershed covered approximately 40 acres near the top of the Santa Catalina Mountains. The watershed extended from about 8400 ft to the top of the mountain at 9157 ft, and included part of the road to an old U.S. Air Force facility. The area drained to the east. Soils were derived primarily from granite parent materials (Whittaker and Niering 1965).

The vegetation consisted of white fir (*Abies concolor*), Douglas-fir (*Pseudotsuga menziesii*), corkbark fir (*A. lasiocarpa* var. *arizonica)*, ponderosa pine (*Pinus ponderosa*), southwestern white pine (*P. strobiformis*), and some aspen (*Populus tremuloides*), Rocky Mountain maple (*Acer grandidentatum*), and several species of oaks, probably *Quercus hypoleucoides* and *Q. rugosa*. The pine was found mostly on the south-facing slopes and ridge tops, and the firs and hardwood species were on the more mesic north-facing slopes and stream bottoms. The watershed contained part of the small even-aged stand of corkbark fir that is indigenous to the Santa Catalina Mountains. Forest inventory data are not available for the watershed, but Niering and Lowe (1984) present species composition and the stand structure information for the major forest types on the Santa Catalina Mountains.

Methods

Seventy snow survey points were located on 12 transects established on the watershed according to stratified random sample design. The watershed primarily faces to the north; only 28 points (40% of

Table 1. Comparison of Snow Depths and Water Equivalents for Selected SCS Snow Courses in Central Arizona on January 15, 1968

Snow Course	Elevation (ft)	Location	Water Equiv (in.)	Snow Depth (in)
Workman Creek	6900	Tonto N.F.	18.4	50
Mingus Mountain	7100	Prescott N.F.	8.6	24
Rose Canyon	**7300**	**Coronado N.F.**	**11.6**	**29**
Fort Valley	7350	Coconino N.F.	6.1	24
Happy Jack	7630	Coconino N.F.	8.7	30
Coronado Trail	8000	Apache-Sitgreaves	11.6	31
Bear Wallow	**8100**	**Coronado N.F.**	**14.7**	**38**
Nutrioso	8500	Apache-Sitgreaves	8.6	25
Hannagan Meadows	9090	Apache-Sitgreaves	16.0	49
Fort Apache	9160	Apache-Sitgreaves	11.6	36

the total) were located on south-facing slopes. Snow depth and water equivalent (the term *water content* was used in past reports) were measured at each point using a standard Federal snow sampler. Density was calculated by dividing water equivalent by depth, and is presented in terms of gm cm^{-3}. Density values for the watershed include all of the measured points with snow cover; average densities for the SCS snow courses are derived by dividing mean depth into mean water equivalent. Watershed surveys in 1968 were conducted on January 14, February 28, March 31, April 21, and May 12. The first survey was conducted before the points could be numbered and tagged; consequently, only 51 points were measured. Unfortunately, only half of the south-facing points were measured at that time, compromising the initial evaluation of aspect differences. The watershed average is used for south-facing values on this date because it is difficult to reconstruct actual conditions from the data. None of the subsequent surveys contained data from all points; between 63 and 66 points were commonly visited.

Watershed data are presented with the 95 percent confidence intervals. Changes in the total watershed snowpack conditions between consecutive survey dates were compared by student t-tests with a Bonferroni correction. T-tests were also used to analyze differences between north and south-facing slopes for the four surveys beginning with February 28. A Type I error of $\alpha = 0.05$ was used in the analyses.

Watershed conditions also were compared to published information from the Bear Wallow and Rose Canyon SCS snow courses (USDA Soil Conservation Service 1981). Statistical comparisons were not conducted because only average values are published. The SCS conducted surveys on these snow courses on a two-week schedule from January 15 through April 1 for 36 years. The typical snow course contains between five and ten measurement points; Bear Wallow contained eight and Rose Canyon had seven points. Both areas are surrounded by old-growth ponderosa pine stands composed of trees 20 inches diameter at breast height and larger (Ffolliott et al. 1996). Overstory density averages 100 ft^2 at Bear Wallow and about 50 ft^2 at Rose Canyon. Bear Wallow is located on a northeasterly aspect and Rose Canyon on a northwesterly aspect; slopes are between 30 and 40 percent. It is important to note that the two snow courses do not appear to represent snowpack conditions in the surrounding forests at the respective elevations, but are more representative of conditions at some unknown higher elevation. These observations are consistent with the findings of Gottfried and Ffolliott (1981) for central and eastern Arizona. Niering and Lowe (1984) divided the ponderosa pine forests in the Santa Catalina Mountains into two categories: the ponderosa pine–oak forest, which contains a large component of *Q. hypoleucoides*, occurs from 7000 to 8000 ft, and the ponderosa pine forest, with a small component of Gambel oak (*Q. gambelii*), occurs from 8000 to 9000 ft. Rose Canyon should be representative of the first category and Bear Wallow, the second.

Unfortunately, detailed meteorological records are not available from the watershed or the snow courses, but data on precipitation and temperature were collected at the Palisades Ranger Station during the winter of 1967–1968 (U.S. Department of Commerce 1968b; Sellers and Hill 1974). The station at 7945 ft is located between the two snow courses and along the main road to the top of Mount Lemmon. These data were used to indicate approximate additional precipitation on the SCS snow courses and the watershed, although exact accumulations were probably different among the areas because of differing elevations, vegetation, and topography.

Watershed and SCS Data

The comparison among the Mount Lemmon watershed and the two SCS snow courses on the Santa Catalina Mountains demonstrates snowpack differences and dynamics from three areas along an elevational gradient. The initial snow survey on the Mount Lemmon watershed on January 14 indicated an average of 15.5 inches of snow water equivalent in a 52.5 inches deep snowpack (Table 2). The greatest depth was 72 inches with 25 inches of water at a point just under the peak. The average density of 0.30 gm cm^{-3} indicates that settling had occurred since the initial storm periods; newly fallen snow usually averages 0.10 gm cm^{-3}. Aver-

Table 2. Mount Lemmon Watershed Average Snowpack Characteristics (with 95% confidence intervals) for the Winter of 1967–1968

Date	Snow Depth (in.)	Snowpack Density (gm cm^{-3})	Snow Water Equiv (in.)
Jan 14	52.53 ± 2.08	0.30 ± 0.02	15.46 ± 1.16
Feb 28	40.80 ± 4.65	0.39 ± 0.01	15.79 ± 1.71
Mar 31	39.63 ± 5.97	0.40 ± 0.02	15.92 ± 2.43
Apr 21	25.10 ± 4.88	0.44 ± 0.01	10.92 ± 2.10
May 12	7.98 ± 3.03	0.51 ± 0.02	4.04 ± 1.51

age water equivalent on the watershed was similar to Bear Wallow, which had 14.7 inches, a value within the watershed average confidence band. The watershed had 3.9 inches more water equivalent than Rose Canyon (Table 1, Figure 1). The differences in snow depth were more pronounced (Figure 2). Snow densities were about 0.40 gm cm^{-3} on the two snow courses, reflecting greater settling than on the watershed (Figure 3).

The February 28 survey measured a small increase of about 0.3 inches of water equivalent on the watershed (Table 2, Figure 1), although average depth had declined almost a foot (Figure 2). Density had increased to 0.39 gm cm^{-3}, reflecting both additional snowfall and periodic day melting and night freezing cycles within the snowpack, even at this high elevation. The changes in average depth and density since January were statistically significant. The Palisades Ranger Station recorded about 5.2 inches of additional moisture between January 15 and February 28 (U.S. Department of Commerce 1968b). Average monthly temperatures of 32.7° F in January and 35.7° F in February (Sellers and Hill 1974) were within the normal range.

The SCS snow courses, which were measured on January 30 and February 15, confirm these fluctuations (Figures 1–3). The Bear Wallow data indicate snow accumulations of at least 2.3 inches of water equivalent between January 15 and January 30, which were not identified on the watershed. This snowpack declined by 4.4 inches of water equivalent and 9 inches of depth from January 30 to February 29, with the largest decrease between February 15 and February 29. No snow fell that month after February 14. The Rose Canyon record indicates minor changes between January 15 and February 15 as accumulations replaced snow water lost through melting and sublimation. The decline between February 15 and February 29 was steepest at Rose Canyon, with decreases of 7.9 inches of water equivalent and 17 inches of depth. Differences between the watershed and the lower elevation SCS snow courses could be because of temperature, solar radiation, and vegetation differences that influence energy dynamics. No pattern appears in the density value fluctuations from the snow courses.

Another view of actual snowpack water equivalent losses between January 15 and February 29 is obtained by considering the 5.2 inches of new snowfall at Palisades. The watershed snowpack then lost at least 4.9 inches of water during this period, even though the data indicate a slight increase. Bear Wallow lost about 7.3 inches and Rose Canyon lost 13.7 inches of water through snowmelt and sublimation.

The watershed snowpack remained relatively stable between February 28 and March 31 (Table 2, Figures 1–3). The three snowpack characteristics were statistically similar for these dates. Snow continued to fall; one point contained 34 inches of water equivalent and 87 inches of depth on March 31. The SCS snow courses, with an additional measurement on March 13, again confirmed snowpack accumulations and melting that were not recorded on the watershed. Palisades recorded approximately 3.0 inches of precipitation between March 1 and March 11, and an additional 0.2 inches later in March. The average monthly temperature in March was 36.7° F. The SCS record indicates that the snowpack at Bear Wallow increased 2.7 inches of water equivalent and 12 inches of depth and Rose Canyon rose 0.9 inches and 4 inches, respectively. The new snow caused average densities to decline. The snowpack on both snow courses declined after March 15, and Rose Canyon was bare by April 1. The last measurement on Bear Wallow was 10.8 inches of water equivalent and 23 inches of snow depth, indicating a density of 0.47 gm cm^{-3} If March precipitation is added, the watershed lost 3.1 inches of water equivalent while Bear Wallow lost 5.0 inches and Rose Canyon lost 6.3 inches since February 29. No information is available on how long snow persisted at Bear Wallow.

The watershed snowpack began to melt more rapidly after March 31 (Table 2, Figures 1–3). The differences between March and April and April and May were statistically significant for all categories. Approximately 1.3 inches of new precipitation fell in April and May, and average monthly temperatures were 41.8° F and 54.1° F, respectively. However, the higher elevation snowpack still contained 4 inches of water equivalent in 8 inches of depth on May 12. The snowpack lost approximately 13.2 inches during this period, when new precipitation is considered.

North and South-Facing Slopes

Snowpack dynamics on the Mount Lemmon watershed are clearer if the dynamics on the north and south-facing slopes are examined separately. Due to the inclination of the sun, south-facing slopes in the northern temperate latitudes experience greater insolation than neighboring north-facing slopes (Barbour et al. 1980). Slope exposure affects solar radiation energy inputs; consequently air, soil, and snowpack temperature regimes,

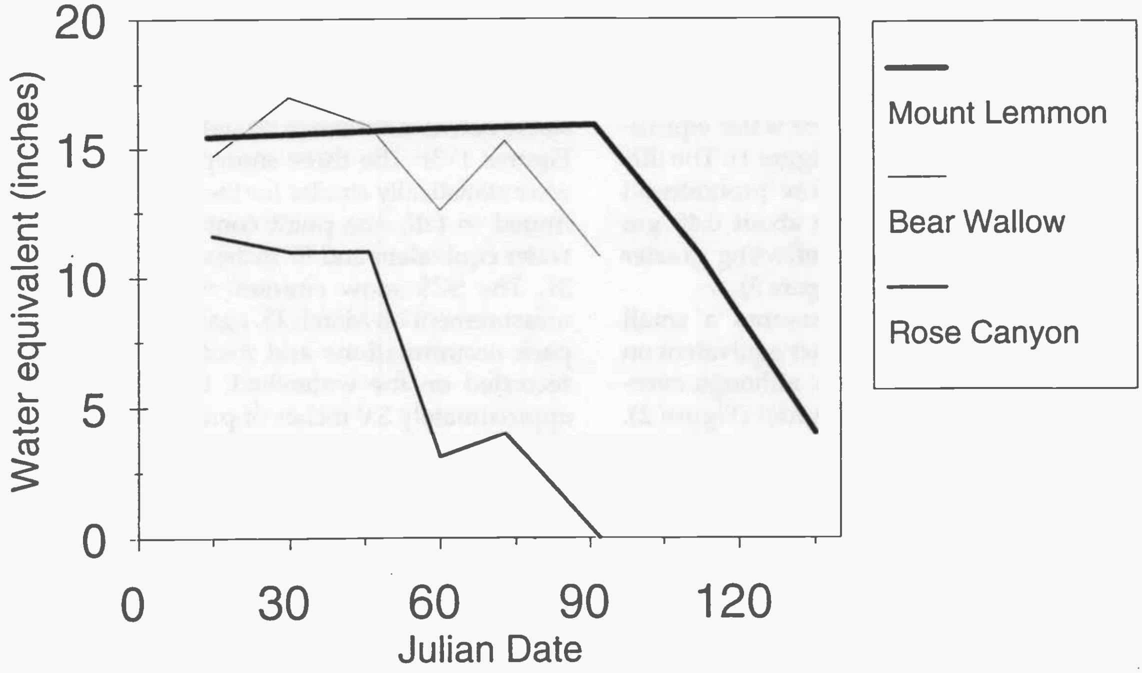

Figure 1. Average snowpack water equivalent on the Mount Lemmon watershed and on the Bear Wallow and Rose Canyon snow courses during the 1967–1968 winter.

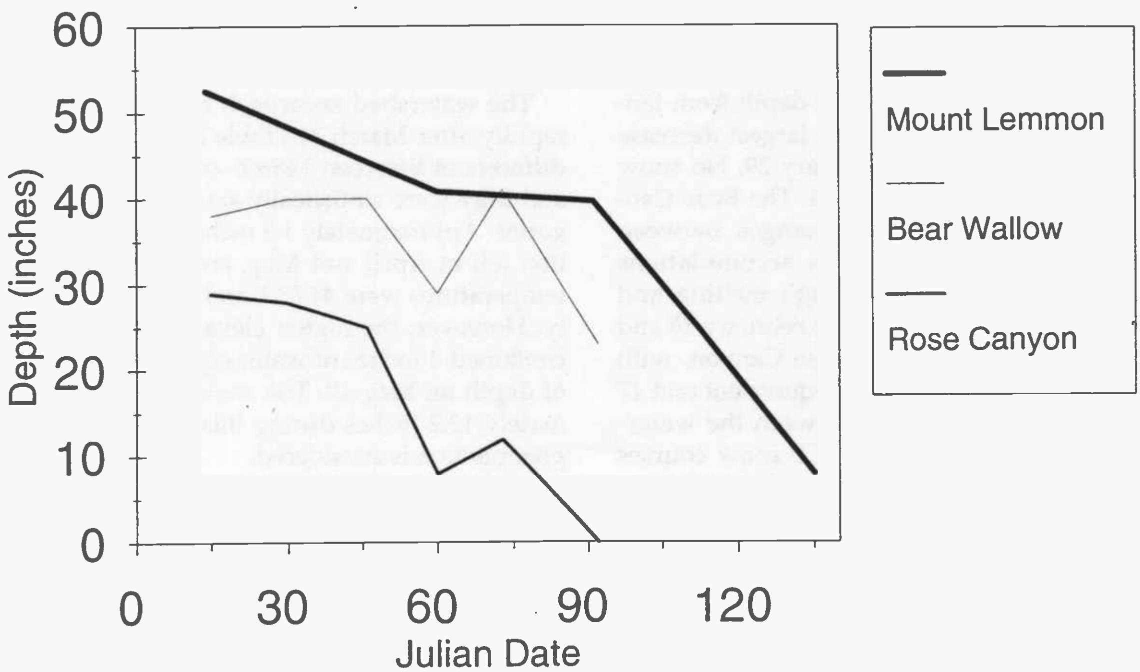

Figure 2. Average snowpack depth on the Mount Lemmon watershed and on the Bear Wallow and Rose Canyon snow courses during the 1967–1968 winter.

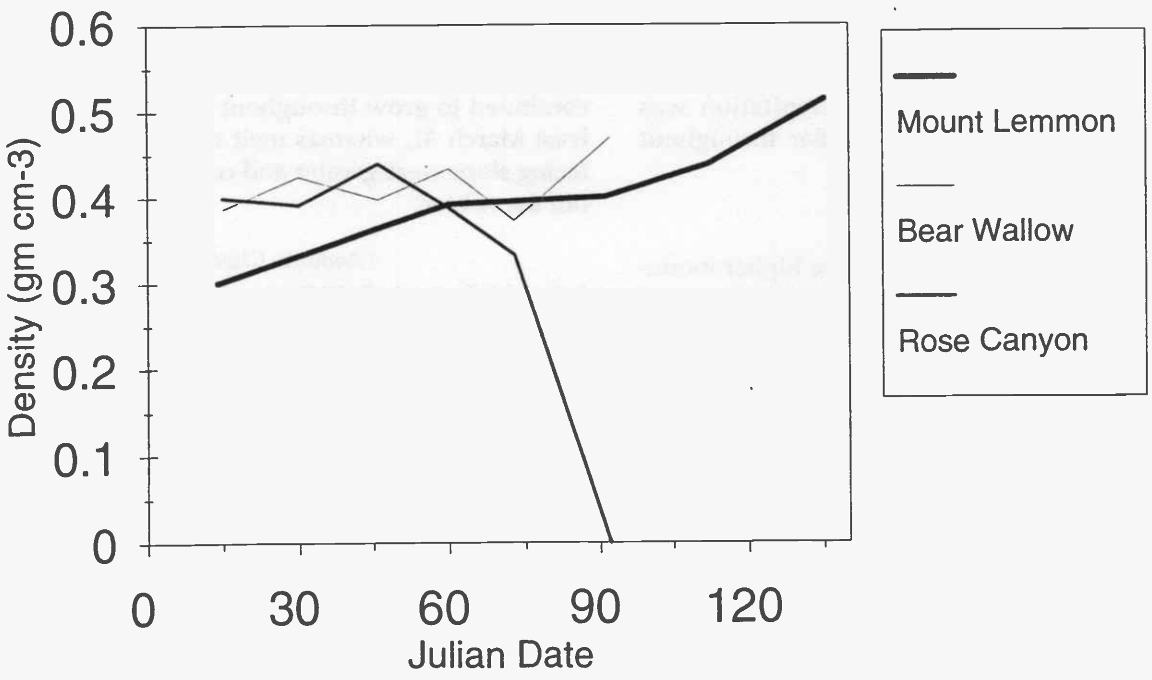

Figure 3. Average snowpack density on the Mount Lemmon watershed and on the Bear Wallow and Rose Canyon snow courses during the 1967–1968 winter.

evapotranspiration, vegetation type, phenology, and density. Although stand data are not available, stands on the south-facing slopes, dominated by ponderosa pine with Douglas-fir, were more open than the fir stands on north-facing slopes.

The watershed and its slopes had similar snowpack conditions on January 14. However, subsequent measurements indicated statistically different slope-related water equivalent and depth differences for each date (Table 3). Snowpack densities were similar for the February, March, and April dates. The snow water equivalent on the north-facing slope rose constantly from January through the March 31 measurement period to 21.2 inches, a net gain of 6 inches. The Palisades Station recorded 8.2 inches of precipitation during the period. Snowpack depth fluctuated but declined from 54.3 and 52.2 inches, while density rose to 0.41 gm cm^{-3} (Table 3). Both snowpack accumulation and ablation processes were occurring. The south-facing slope had a decline over this period to about 8.9 inches of water equivalent, a loss of about 6.6 inches, and to 23 inches of depth, a loss of approximately 29.5 inches. Density was 0.39 gm cm^{-3}. Total losses of about 2.2 inches from the north-facing slope and 14.8 inches from the south-facing slope are estimated if precipitation at Palisades is considered. Twenty-nine percent of the south-facing points were bare on March 31 compared to 5 percent on the opposite slope.

Both slopes show rapid melting after March 31 (Table 3). The north-facing slope snowpack declined by 14.2 inches of water equivalent and 38 inches of depth by May 12. Losses were about 15.5 inches, if the additional 1.3 inches of precipitation is considered. Only 40 percent of the points were bare when surveys were concluded. Sixty-seven percent of the south-facing points were bare by April 21 and all were bare by May 12, having lost

Table 3. Snowpack Characteristics Differences Between North and South-Facing Slopes (Averages with Standard Errors)

Date	Depth (in.)	Density (gm cm^{-3})	Water Equiv (in.)
North-facing slopes			
Jan 14	54.30 ± 0.94	0.28 ± 0.01	15.24 ± 0.21
Feb 28	50.28 ± 2.02	0.38 ± 0.01	19.12 ± 0.68
Mar 31	52.22 ± 3.06	0.41 ± 0.01	21.23 ± 1.26
Apr 21	36.90 ± 2.14	0.44 ± 0.01	16.04 ± 0.88
May 12	13.86 ± 2.20	0.51 ± 0.02	7.01 ± 1.08
South-facing slopes			
Jan 14	52.53e	0.30e	15.46e
Feb 28	27.93 ± 3.54	0.41 ± 0.01	11.27 ± 1.41
Mar 31	23.00 ± 3.82	0.39 ± 0.02	8.89 ± 1.46
Apr 21	9.35 ± 2.88	0.44 ± 0.02	4.09 ± 1.27
May 12	0.00	0.00	0.00

e = estimated value

8.9 inches of water equivalent and 23 inches of depth over the 42 days. Water equivalent losses were 10.2 inches when new precipitation was added. Snow densities were similar throughout the watershed and its slopes.

Conclusion

Snowpacks develop annually in the higher mountains of the Madrean Province in southeastern Arizona. Although this moisture might not greatly impact regional water supplies, it is important for recreation and local communities, and for sustaining the important Madrean riparian, woodland, and forest ecosystems. Snowpack information is important for managers and individuals who need access into high-elevation areas. Data on snowpack characteristics and dynamics within these isolated mountain ranges are scarce. The availability of snow data from the Mount Lemmon watershed contributes to this knowledge, and to the understanding of the importance of snow in these mountain ecosystems. Measurements from the watershed, combined with records from the SCS snow courses at Rose Canyon and Bear Wallow, provide an elevational gradient of snow data from above 7000 ft in the lower ponderosa pine–oak forests, through the upper ponderosa pine forests to the mixed conifer forests at almost 9200 ft on the top of the watershed. Because extreme conditions, both wet and dry, are more common in the Southwest than the average situation, knowledge of snowpack accumulation, and especially melt dynamics in a wet year, can be important for planning and activities by land, wildlife, and water managers.

The documentation of the snowpack conditions on the Santa Catalina Mountain watershed during this winter confirmed many of the recognized relationships between snowpack dynamics and elevation or slope. More snow fell at the higher elevations and the snowpack remained on the ground longer into the spring; the entire watershed did not have significant melting until after April 1. Sixty percent of the sample points on the north-facing slope still contained snow on May 12. The snowpack at elevations represented by Bear Wallow began melting rapidly by March 15, although snow still was present on April 1. The lower ponderosa pine–oak stands represented by Rose Canyon were bare by April 1; major melting began soon after February 15. Examination of snowpack measurements from the north and south-facing slopes on the watershed confirms the importance of aspect for snow accumulation and ablation. The snowpack on the north-facing slopes continued to grow throughout the winter until at least March 31, whereas melt rates on the south-facing slope were greater and continuous throughout the winter.

Literature Cited

Baker, M. B., Jr., L. F. DeBano and P. F. Ffolliott. 1995. Hydrology and water management in the Madrean Archipelago. Pages 329–337 in L.F. DeBano, P. F. Ffolliott, A. Ortega-Rubio, G. J. Gottfried, R.H. Hamre and C. B. Edminster (Technical Coordinators), Biodiversity and management of the Madrean Archipelago: The Sky Islands of southwestern United States and northern Mexico. USDA Forest Service, General Technical Report RM-GTR-264.

Barbour, M. G., J. H. Burk and W. D. Pitts. 1980. Terrestrial plant ecology. Benjamin/Cummings, Menlo Park, CA. 604 pp.

Ffolliott, P. F., G. J. Gottfried, and M. B. Baker, Jr. 1989. Water yield from forest snowpack management: Research findings in Arizona and New Mexico. Water Resources Research 25: 1999–2007.

Ffolliott, P. F., G. J. Gottfried, and M. B. Baker, Jr. 1996. Role of snow in the hydrology of the Madrean Province in southeastern Arizona. Hydrology and Water Resources in Arizona and the Southwest 26: 35–37.

Gottfried, G. J. and P. F. Ffolliott. 1981. Evaluation of the use of Soil Conservation Service snow course data in describing local snow conditions in Arizona forests. Hydrology and Water Resources in Arizona and the Southwest 11: 55–62.

Niering, W. A. and C. H. Lowe. 1984. Vegetation of the Santa Catalina Mountains: Community types and dynamics. Vegetatio 58: 3–28.

Sellers, W. D. and R. H. Hill. 1974. Arizona Climate: 1931–1972. University of Arizona Press, Tucson. 616 pp.

U.S. Department of Agriculture, Soil Conservation Service. 1981. Summary of snow measurements for Arizona and pertinent portions of New Mexico: 1938–1980. USDA Soil Conservation Service, Washington, D.C. 179 pp.

U.S. Department of Commerce, Environmental Science Service Administration. 1968a. Climatological data: Arizona, December 1967. U.S. Department of Commerce, Environmental Science Service Administration, Environmental Data Service, Washington, D.C. 71.

U.S. Department of Commerce, Environmental Science Service Administration. 1968b. Climatological data: Arizona, 1968. U.S. Department of Commerce, Environmental Science Service Administration, Environmental Data Service, Washington, D.C. 72.

Whittaker, R. H. and W. A. Niering. 1965. Vegetation of the Santa Catalina mountains, Arizona: A gradient analysis of the south slope. Ecology 46: 429–452.