SNOWPACK DYNAMICS IN AN OPENING AND A THINNED STAND IN A PONDEROSA PINE FOREST

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Snow that accumulates in high-elevation forested watersheds is an important source of water for downstream municipalities, industries, and agricultural activities. Streamflow and water storage impoundments in the drier regions of the western United States depend on snowmelt. Troendle (1983) estimated that almost 90 percent of the total annual water yields in the Rocky Mountain Region, which includes Arizona and New Mexico, are derived from snowmelt. One estimate indicates that as much as 5,103,630 acre-feet (6.3 billion cubic meters) of water can be in storage in the snowpacks prior to snowmelt (Ffolliott et al. 1989). Snowpacks in the Southwest differ from those in more northern mountains. Most southern snowpacks will experience some melting throughout the winter and, at lower elevations, the snowpack often can disappear between storms (Gottfried et al. 2002). Snowpacks in northern areas tend to accumulate throughout the winter and melt gradually during the early summer.

Foresters and water managers have considered the potential of augmenting streamflow by managing forests to increase snow accumulations and to modify snowmelt runoff. Troendle (1983) reviewed the scientific literature pertaining to the potential for water yield augmentation from snowpack management in the West. Ffolliott et al. (1989) conducted a similar review of snow research in the Southwest. One prime strategy is to create openings within the stand. Research has generally shown that smaller openings, approximately 1 to 3 H (tree height) in diameter, were most efficient in accumulating snow and in delaying snowmelt (Troendle 1983). Ffolliott et al. (1965) and Hansen and Ffolliott (1968), working in an Arizona ponderosa pine (*Pinus ponderosa* Laws.) forest, found that clearcut openings and strips of between 1.5 H and 2 H increased snow accumulation and increased snowmelt rates and daily water losses. Openings tend to change the dynamics of storm winds moving over the forest canopy resulting in more turbulence and greater snow falling into the openings. More snow accumulates under a thinned forest canopy depending on the residual density, because less snow is intercepted by the tree crowns (Gary and Troendle 1982.)

An important objective of forest management in the Southwest, particularly in Arizona, in the 1960s was to increase streamflows and productivity of forest lands for multiple resources. Watershed experiments were established in the ponderosa pine and mixed conifer forests at Beaver Creek, south of Flagstaff (Baker 1986, Baker and Ffolliott 1999), on the Sierra Ancha Experimental Forest in central Arizona (Gottfried et al. 1999a) and in the White Mountains of eastern Arizona (Gottfried et al. 1999b) to evaluate the potential of achieving these goals. As part of this effort, silvicultural treatments were conducted in the ponderosa pine stands on the West Fork of Castle Creek, an experimental watershed in the Apache-Sitgreaves National Forests of eastern Arizona.

Forest snowpack management designed to delay snowmelt may become an important concern in the future as projected increases in global warming develop. Historically deep snowpacks may not develop in the future as rain replaces snow at middle and higher elevations and higher temperatures cause rapid melting. Intermittent snowpacks and resulting runoff changes, such as those reported for Sierra Ancha (Gottfried et al. 2002) will become more common. These watersheds are between 6,590 and 7,724 ft in elevation. The change could result in earlier peak streamflows and longer fire seasons.

The objective of this paper is to examine the snowpack record for a typical irregularly-shaped opening of about 300 feet in diameter in the West Fork of Castle Creek and to compare the results with those from an adjacent forested area where thinning removals had been minimal. Records for five years are compared. Results are compared to meteorological records and data from the historic USDA Soil Conservation Service (now Natural Resources Conservation Service) Beaverhead Snow Course (Jones1981).

TREATMENT PRESCRIPTION

The Castle Creek complex, located about 12 miles south of Alpine in the Apache-Sitgreaves National Forests, consist of two watersheds, the West Fork and the East Fork. The watersheds occur between 7,835 and 8,580 ft in elevation, where average annual precipitation is about 27 inches. Each watershed contains a 120-degree v-notch weir. The standard watershed experimental approach uses paired watersheds where one watershed is treated and the other is not. A statistical relationship is established between runoff from the two areas prior to treatment and then compared to a similar relationship developed for a number of years following treatment.

One-sixth of the forest on the 900-acre West Fork watershed was harvested in 1966 and 1967 to create

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openings to improve stand conditions by removing groups of diseased and over-mature trees and the remaining areas were thinned to remove high-risk, poor trees and to release potential crop trees. The goal was to initiate a commercial forest management operation with a 120-year rotation and a 20-year cutting cycle. Under this system one-sixth of the watershed would be cleared every 20 years. Another objective of the treatment was to improve deer and elk habitats. The hypothesis was that the openings would contribute to water yield improvement because of reduced evapotranspiration and, because the differences in height between the residual stand and the openings, would create aerodynamic forces that would result in increased snowpack accumulations. It was assumed that the thinned forest might use less water than the unharvested stand and also contribute to increased streamflows although this was not tested. However, any increase in water would depend on residual stand density since a dense residual stand will utilize any additional water on site, especially in dry years. The original stand had about 135 ft^2 of basal area per acre which was reduced to about 63 ft^2/acre by the harvest. The treatment resulted in a significant increase in water yields from the watershed of about 0.5 inch or about 30 percent (Gottfried et al. 1999b). The increase persisted for more than 21 years until evaluations were concluded. The benefit of the openings would decline as the new trees grow in height and the difference between them and the surrounding trees decline.

MICROMETEOROLOGY STUDY

The first hypothesis was that the openings would contribute to augmented streamflow by reducing the evapotranspiration demands as stated above. The replacement grasses, forbs, and tree regeneration would utilize less water than the original forest. The reduced demand would also result in more rapid soil recharge and more efficient movement of water into the stream channels. Thompson (1974) established micrometeorological stations in a cleared forest opening, a thinned forest, and a native wet meadow or cienega in West Fork. The three sites were relatively close to each other. He measured net radiation, temperature, vapor pressure, and soil heat flux to calculate evapotranspiration by the Bowen ratio equation. He used three years of data to calculate evapotranspiration for a 150-day growing season. The forest used 19.4 inches, the opening used 15.3 inches, and the cienega used 13.2 inches. Thompson then applied these values to the acreage in each class on the watershed and calculated watershed evapotranspiration at 18.4 inches. This was similar to the 20.2 inches calculated for the period by subtracting runoff from precipitation. The 4.1 inches difference between the forest and opening evapotranspiration values confirms that clearing the forest results in less water used.

SNOW STUDY

Methods

The second hypothesis concerned the role of forest openings in efficiently accumulating snow and modifying snow ablation in the spring. The snow study was established in the opening and adjacent thinned forest experimental sites that were studied by Thompson (1974). The forest site was north of the opening. Six snow courses were established in each area, three running northeast to southwest and three running northwest to southeast (Figure 1). Each site contained about 77 snow survey points. The opening was approximately 300 ft in diameter or about 2 acres in size. The clearing was not a true circle but included open areas that extend away from the center. Lines were extended into the surrounding forest to study possible edge effects on the snowpack. The amount of water in a snowpack is described in terms of snow water equivalents in inches. Snow was measured at each point to determine depth and snow water equivalents using a Federal snow tube. Care was taken to insert the tube in a different place at each point on each visit. Snow was measured in 1968, 1969, 1973, 1974, and 1975 when sufficient snowpacks developed. There were generally eight to nine surveys in a season except in the last two years when the snowpack essentially disappeared by the end of February. Snow measurements only indicate the difference between two dates; they do not indicate fluctuations (gains and losses) during the period. Figure 2 shows the winter precipitation by year from the Log.

Canyon recording rain gauge which was established as part of the micrometeorology study and located within the forest opening southeast of the tower (figure 1). Total winter precipitation accumulations at the Log Canyon gauge (figure 2) were greater than those reported for the individual snow measurement years because they are for the entire period between December 1 and April 30. Precipitation for each year when snow was sampled only indicates the period between the first snow measurement and the last measurement (figures 3 and 4). This also reflects the basic differences between snow course data and point precipitation data as explained by Ffolliott et al. (1965). Snow water equivalent data from the two study sites were compared to the similar record from the Beaverhead snow course measured by the USDA Soil Conservation Service. The course, which is located in a meadow within the East Fork of Castle Creek, to the east of the study sites, was measured twice a month from January 15 until April 1 or until snow had disappeared. The course, which was established in 1937-38, is now being monitored as part of the SNOTEL system.

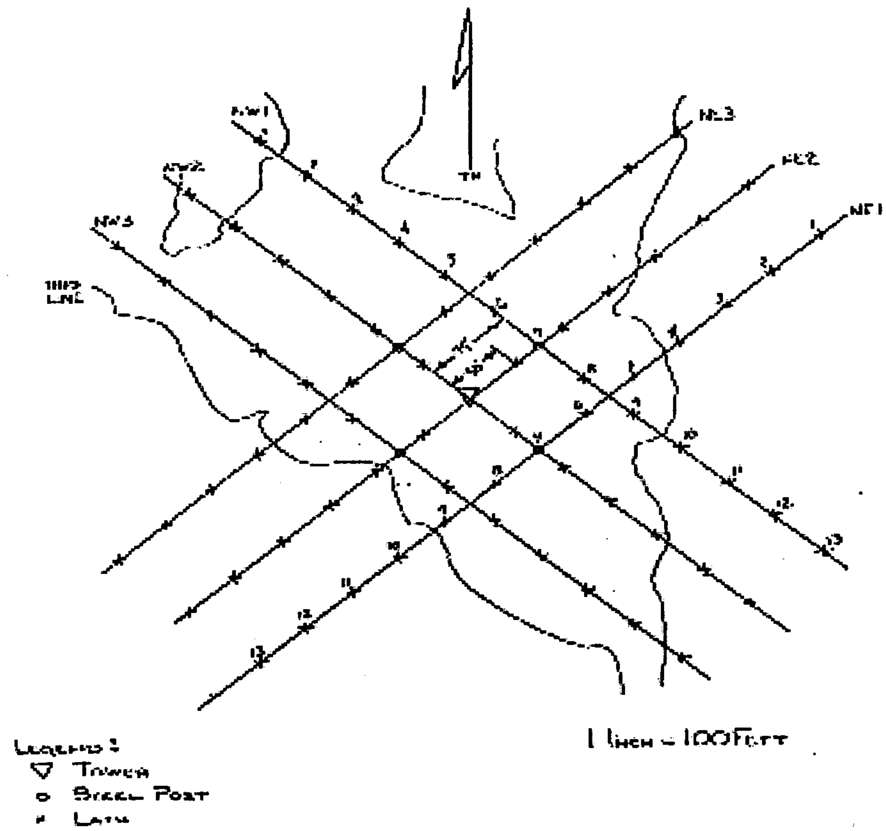

Figure 1. Map of the forest opening at Castle Creek West Fork and the layout of the snow survey lines. Survey points are 50 ft apart and parallel lines are 75 ft apart. The tree line is shown. The same design was used in the forested plot.

The tree cover was measured on every other snow point using a 10 BAF wedge. Points in the center of the opening were not measured. There were 21 points in the opening plot and 41 in the forest plot. The forest surrounding the opening contained 105 trees/ac. and 40 ft^2/ac of basal area. Sixty-nine percent of the trees were ponderosa pine, 21 percent were Gambel oak (Quercus gambelii), and 10 percent were aspen (Populus tremuloides). The forest contained 133 trees/ac and 58 ft^2/ac. Ninety-four percent of the trees were ponderosa pine and the rest were Gambel oak. The average tree height was calculated to be about 73 ft in the open site and 63 ft in the forest site. A greater number of large ponderosa pine trees had been left in the stand surrounding the opening. The letter H is used in forest snow research to represent the height of the average tree and openings are described in terms of multiples of H. The average 1.5 H of the trees surrounding the opening at Castle Creek was calculated to be 110 ft. Much of the 300 ft diameter opening would be under the influence of the border. The influence zone, especially of the southern border, varies throughout the season as the sun angle changes. The shaded area is larger in the winter and declines as spring approaches and the sun angle increases.

The snow water equivalent data were compared visually without statistical analyses. However, paired t-tests were used to compare conditions for the two sites and the Beaverhead course at the beginning of the season and at the point of maximum accumulations. The assumption was that all three areas were affected similarly by the same storms.

Results and Discussion

The amount of snow water equivalents fluctuates during the winter depending on new snowfall and continuing snow evaporation, sublimation from the snowpack surface, and snowmelt. Snowmelt recharges the soil mantel and the excess contributes to early streamflow. Precipitation and the amount of snow water during the five winters were different (figure 2). The changes in snow water equivalents between the forest opening and the forested plots for the five years are presented in figures 3 and 4, along with the accumulated precipitation measured at Log Canyon from December 1 through the date of the last survey (figure 2). Most of the snow in the winter of 1967-1968 fell during a historical December storm that produced more than 9 inches of snow water equivalent at Castle Creek (figure 3). An additional 0.84 inch fell in January before surveys began. Measurements on January 30, 1968 indicated that the snow depth and water equivalents were "fairly" uniform across the open plot. Average snow water equivalents were 2.76 inches greater in the opening than in the forest. Snow interception by the forest canopy probably contributed to some of the early differences between sites. However, interception losses are not a significant factor in southwestern forests because most snow water eventually reaches the ground by snow slide, wind erosion or melting snow water dripping from the canopy (Ffolliott et al. 1989).

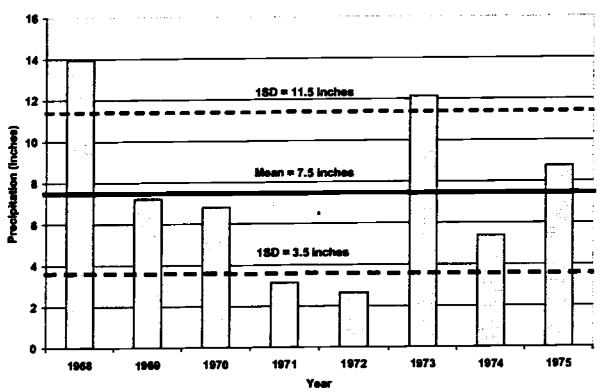

Figure 2. Precipitation for the December through April period at the Log Canyon recording precipitation gauge in the forest opening. The graph presents the average with the one standard deviation lines.

The record 1968 snowpack declined in the opening throughout the season, except for the influence of a March storm (figure 3). The initial reading indicated that more snow was present in the snowpack than was measured at the Log Canyon gauge, which is located in the forest opening. This could reflect some snow drifting within the plot during and following a storm. Ffolliott et al. (1965) determined that snow tube measurements over an area are more accurate than gauge measurements because turbulence and eddy currents could reduce the amount of water collected at a single point. Bare points were noted in the opening during the March 27 survey. Forty-two percent of the points were bare on April 5 and 77 percent were tallied as bare during the last survey on April 9. Most of the remaining snow was within 50 to 100 ft of the tree line.

The forest plot had a complete snow cover on January 31, 1968 but the number of bare points increased after that date except for the period after the storm of March 12. The snowpack in a forest declined sooner and more rapidly than the one in an opening and then stayed about the same until final snowmelt (figure 3). The rapid melt is related to solar radiation that is "trapped" below the canopy and re-radiated to the snow surface rather than escaping into the atmosphere. This aspect of the radiation budget was not measured. Approximately 40 percent of the points were bare by March 5, 58 percent by March 20, and 82 percent by March 27. The forest points were completely bare by the April 5 survey.

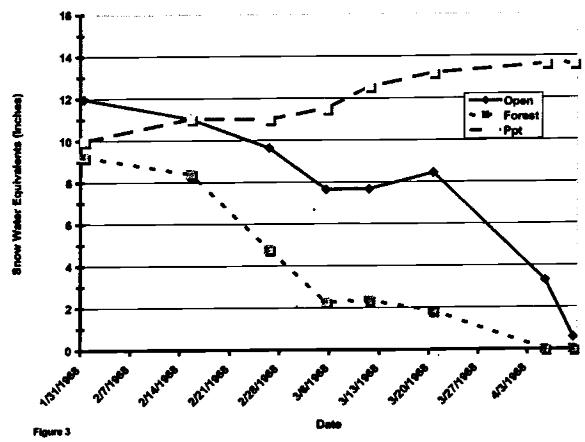

Figure 3. Snowpack fluctuations in snow water equivalents for the forest opening and forest during the winter of 1968. The accumulated precipitation from the Log Canyon gauge is shown.

Data for 1969 (figure 4A) was typical of most years where the snowpack fluctuated but generally accumulated throughout the winter. The forest opening accumulated snow until March 18 when increased temperatures resulted in a rapid decline in snow water. Snow water equivalents in the forest declined throughout the season except for the effects of the late winter storm. Almost 60 percent of the forest points were bare by February 5 while only 6 percent were bare in the opening site.

Snow accumulations during 1973 differed from those during 1968 (figure 3) because snow accumulations in 1973 increased throughout the season until their total reached 8.3 inches (figure 4B). Accumulations in February and March were 7.10 inches. The snowpacks in the forest and opening were similar at the beginning of the season. Although the forest water content increased during the season, losses exceeded gains. Some scattered bare points were noted during the early surveys but general snowmelt was not noticed until the April 2 measurements. Snowmelt increased after March 20. The date when all snow had melted was not determined. Surveys were terminated in 1973-1975 once local observations by personnel from the Apache-Sitgreaves National Forests indicated that the plots were essentially bare.

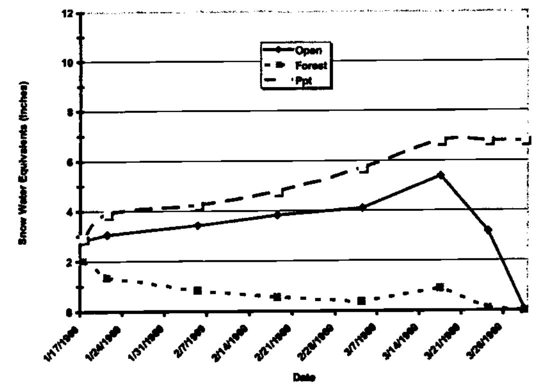

Figure 4A-D. Snowpack fluctuations in snow water equivalents for the forest opening and forest during the winters of 1969 (A), 1973 (B), 1974 (C), and 1975 (D). The accumulated precipitation from the Log Canyon gauge is shown.

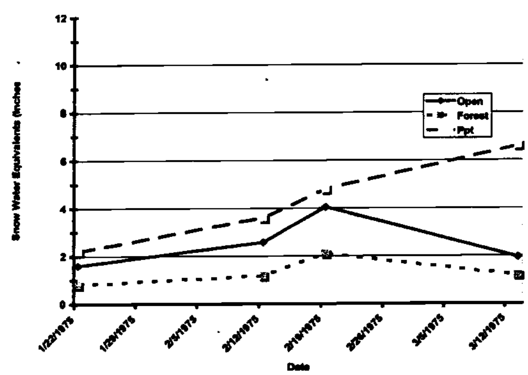

Figure 4B 1973

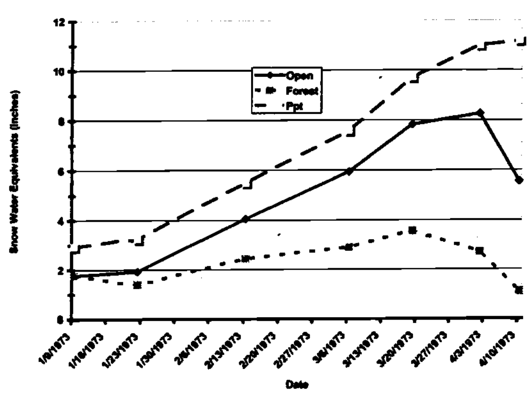

Figure 4C. 1974

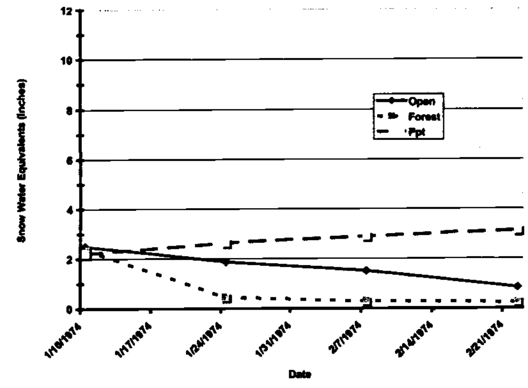

Figure 4D. 1975

The total water content of snow accumulations during 1974 and 1975 winter seasons (figures 4C and 4D, respectively) were "typical amounts of long-term average winter precipitation for the site which was 7.5 inches (figure 2). A general snow water equivalent decline was measured in 1974 (figure 4C); 63 percent of the forest points were bare by January 24 and 87 percent were bare by February 22. The opening had 2 percent and 64 percent bare on those dates. The amount of water in the snowpack initially increased in the opening in 1969, 1973, and 1975 (figures 4A, 4B, and 4D) and melted rapidly during the late winter or spring. Winter precipitation in 1975 was above the average for the eight-year study period (figure 2), and no bare points were measured early in that season because of frequent storms. The early snow water equivalent decline in 1975 may, in part, reflect the less intense sampling schedule that could have missed larger snow accumulations between February 19 and March 13.

All five years of data confirm that more snow accumulates in the forest opening relative to the adjacent thinned forest stand. While snowmelt and other water losses occur in the opening throughout the winter when compared to the accumulated precipitation, a substantial amount of snow remains on site until mid-March or early April when air temperatures rise and snowmelt accelerates. This is apparent in the data from 1968, 1969, and 1973 when most of the winter was monitored. The rapid snow melt provides efficient movement of water through the recharged soil into the stream channels. The flush of snow-melt would be less from the thinned forest stands. Isolated snow patches that remain after the period of rapid melt do not contribute to runoff unless they are close to the channel because the soil profile has begun to dry due to evapotranspiration and drainage. These patches do provide a local benefit to the vegetation.

Comparisons with Beaverhead Snow Course

The Soil Conservation Service Beaverhead snow course (Jones 1981), which is located in the East Fork of Castle Creek downstream from the snow study site, also provides a history of snowpack dynamics during the five years when the forest opening and forest were measured. The Beaverhead snow course was established to provide an indication of snowpack dynamics in the Castle Creek area which includes the headwaters of the Gila and Salt Rivers. Beaverhead is affected by the same storms as the two experimental sites; however, the amounts of snow water equivalents measured at Beaverhead were similar but not identical to the study area. It would be surprising if data from the experimental sites and the snow course were identical. Each experimental site on Castle Creek contains 77 points while the standard SCS snow course contains between eight and ten points. Beaverhead is in a relatively large opening where wind could be an influence especially after storms and before the snow crust develops. One example of this difference is that the peak in 1973 was 8.3 inches in the forest opening study site and 6.8 inches at Beaverhead. The shapes of the lines on graphs of snowpack fluctuations also may be different. Differences can be related to the dynamic nature of the snowpack between measurement dates which often differed between the experimental areas and the SCS snow course.

Several comparisons were made between the data collected by the Soil Conservation Service at Beaverhead and those collected on the forest stands and openings at Castle Creek. These comparisons are based on the assumption that all three areas were affected in the same way by the storm patterns. Linear regressions of maximum snow water equivalent data were developed between Beaverhead (the independent variable) and the forest opening and the forest site. Both regressions were significant and had coefficients of determination between 0.91 and 0.93. Differences between the two lines were not compared since the confidence bands were large because of the small sample size ($n= 5$).

Paired t-tests were conducted on initial snow water equivalent data and on maximum accumulation data. The initial measurement data did not indicate any significant differences between Beaverhead and the forest or between Beaverhead and the opening. The same type of analysis at the time of maximum accumulations indicated that Beaverhead and the opening were similar but that Beaverhead and the forest and the opening and the forest at Castle Creek were significantly different at the 5 percent level.

CONCLUSIONS

This paper provides a look at snowpack dynamics within a ponderosa pine forest opening and an adjacent thinned ponderosa pine stand in eastern Arizona. The data show that more snow accumulated in the forest opening than in the forest and that the snow remained on the soil surface longer into the spring. This relationship has been observed in other western forests. Linking the snowpack information to the results from Thompson's (1974) evapotranspiration study validate the hypothesis that openings contribute to the sustained increased runoff from Castle Creek West Fork. We do not have information about the contributions of the thinned stands to runoff on Castle Creek. However, a heavy thinning of a ponderosa pine forest on Watershed 17 at Beaver Creek in Arizona produced significant increases in streamflow for a 10-year period (Baker 1986). Studies in other locations (Gary and Troendle 1982) indicate changes in snowpack accumulations related to stand density which could affect soil moisture recharge and streamflow.

The results, which provide information for interpreting the impacts of forest overstory modifications on runoff, are based on data that were collected more than 30-years-ago. Files stored at the Rocky Mountain Research Station locations in Flagstaff and Phoenix contain additional weather, snowpack, and streamflow data that could be used to further explain the snowpack dynamics that were observed. It would be interesting, for example, to try to link snowmelt to fluctuations in the watershed's hydrograph. The original study actually contained six other openings ranging from 0.5 to 15 acres in size. These data have not been analyzed. Similar files of relevant data from other research studies exist in cabinets at governmental agencies and universities. Archiving and, where appropriate, analyzing them can be a relatively easy and cost effective way of advancing science. Cooperative efforts between the Forest Service and university faculty and students should enhance these efforts by providing new insights and approaches to the efforts. The data could serve as a basis for developing or validating predictive computer simulation models. Knowledge o historical snowpack dynamics and streamflow regimes will be important in the future as we attempt to gauge and monitor projected climate change scenarios on snowpacks and streamflow from these watersheds that provide water to ecosystems throughout the Southwest and to downstream and local human populations. The enhancement of snow accumulations and water production by modified silvicultural prescriptions may again become important forest management goals.

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