SNOWPACK-RUNOFF RELATIONSHIPS FOR FORESTED MID-ELEVATION WATERSHEDS AND A HIGH-ELEVATION WATERSHED IN ARIZONA

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ABSTRACT

Snowmelt from higher elevation forested watersheds is a major source of runoff for most of the rivers in the southwestern United States. Snowpacks in the Southwest melt intermittently throughout the winter. At some mid-elevation locations, between 2,135 and 2,285 m (7,000 and 7,500 ft), snowpacks appear and disappear, depending on the distribution of storms and temperature fluctuations during the winter. Snowpacks at higher elevations may experience periods of melting but generally accumulate snow throughout the winter with most snowmelt occurring during the spring. The USDA Natural Resources Conservation Service (NRCS) maintains a system of measuring stations to index snow conditions and predict snowmelt runoff. Peak snow water equivalent data from NRCS stations have been related to snowmelt runoff volumes and mean daily peak flows for the three mid-elevation Workman Creek watersheds north of Globe, Arizona and for the high-elevation East Fork of Willow Creek in the White Mountains of eastern Arizona. The statistically significant relationships for Workman Creek are being used as a basis to measure the effects of the Coon Creek Wildfire on watershed hydrology and to estimate winter streamflows for the years when the installations were closed. The comparisons between mid and high-elevation watersheds will increase our knowledge of snowmelt dynamics in the Southwest.

INTRODUCTION

Water availability is a critical issue for the continued development of the southwestern United States. Knowledge of streamflow timing is important to efficient impoundment and distribution. Snowmelt from higher elevation forested watersheds is a major source of runoff for most of the rivers in the western United States. Approximately 370,000 to 629,000 ha-m (3.0 to 5.1 million ac-ft) of water are stored in Arizona and New Mexico snowpacks before spring snowmelt (Ffolliott et al. 1989). However, snowpack conditions in the Southwest are variable; years of high and low snowpack accumulations are more common than average years. Southwestern snowpacks, unlike those in northern regions, melt intermittently throughout the winter. At some intermediate, mid-elevation locations (generally between 2,135 and 2,285 m (7,000 and 7,500 ft)), the snowpack appears and disappears, depending on the distribution of storms and temperature fluctuations during relatively dry winters. Snowpacks at higher elevations (generally above 2,440 m (8,000 ft)) may experience periods of melting but generally accumulate snow throughout the winter with most snowmelt occurring during the spring.

The relatively large number of wildfires that occurred throughout the southwestern United States in the years 2000 and 2002 renewed interest about the effects of stand replacing fires on watershed characteristics and responses. In the early spring of 2000, the Coon Creek Fire overran the three Workman Creek watersheds within the Sierra Ancha Experimental Forest in central Arizona. The presence of weirs and a flume provided an opportunity to study the effects of this wildfire on peak flows, water quantity and quality, and sedimentation. This information is lacking in the Southwest, and its acquisition will allow land and water managers to assess flood risks and to plan post-fire restoration and protection strategies in the future. It also could aid managers in estimating water yields from large burned areas. The Rocky Mountain Research Station and Tonto National Forest reopened the Workman Creek installation in June 2000 to obtain these data for a five-year period.

The Workman Creek installations, including climatic stations, were operated from late 1938 through 1983. The USDA Natural Resources Conservation Service (NRCS), formally the Soil Conservation Service (SCS), has maintained a snow course and, subsequently, a snow telemetry station (SNOTEL) at Peterson Meadow within the Middle Fork of Workman Creek since 1951. This site, at 2,100 m (6,900 ft) in elevation, serves as an index of

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snowpack dynamics in the Sierra Ancha Mountains, which are adjacent and northeast of Roosevelt Reservoir. Snow courses generally reflect snow conditions at higher elevations (Gottfried and Ffolliott 1981) and the Workman Creek snow course is representative of snowpacks at intermediate elevations. The Coon Creek Fire destroyed most of the old-growth forest on Middle Fork, which had served as the hydrological control for the various experiments. However, the area immediately adjacent to the NRCS station was not severely burned. Paired data were collected from the snow course and SNOTEL for 10 years until the snow course was deactivated in 1991.

The primary objective of this study was to determine the historical relationship between the NRCS snow water equivalent data measured on snow courses and (1) snowmelt runoff and (2) average flow rate for the day of maximum runoff. SNOTEL data were not available for most of the period of interest at Workman Creek and are not used in the analyses for Workman or Willow Creeks. A statistically significant relationship could provide another tool for evaluating changes related to the fire and for predicting streamflow parameters for future snowmelt periods. The relationship also could be used to check if the fire influenced post-fire data from the NRCS station. It would be useful in interpreting the effects of past treatments and providing previously unavailable information about snowpack-runoff relationships for the Workman Creek watersheds. The streamflow information could be extrapolated to other mid-elevation watersheds where intermittent snowpacks occur. The secondary objective was to compare the relationships developed for the mid-elevation Workman Creek watersheds with similar relationships developed for the high-elevation watershed on the East Fork of Willow Creek that is at approximately 2,745 m (9,000 ft) where snowmelt primarily occurs in the spring. A comparison among forested watersheds at different elevations should improve our understanding of snowmelt characteristics in the Southwest.

BACKGROUND

The Workman Creek (NRCS ID. 10S01) and Hannagan Meadows (NRCS ID. 09S11) snow courses and SNOTEL stations are part of a system that the NRCS maintains throughout the western United States to monitor snowpack conditions. SNOTEL stations collect snow and meteorological data and transmit them electronically to central locations. The NRCS snow courses and installations, which are usually located in forest openings, are representative of high mountain locations and provide an index of snow conditions within a river basin. Long-term snow course and related meteorological data are correlated with streamflow to predict future runoff from water stored in the snowpack. The snow survey effort in Arizona began in late 1937 to forecast streamflow in the Salt and San Francisco Rivers (Jones 1981).

In the late 1950s and 1960s, the USDA Forest Service's Rocky Mountain Forest and Range Experiment Station (now the Rocky Mountain Research Station) embarked on a watershed management research effort to evaluate the effects of a variety of vegetation management treatments on water yield augmentation, timber production, wildlife habitat, and livestock forage production (Baker 1999). Since snow is an important component of the hydrological regime in higher elevations, most of the forested experimental watersheds contained snow-sampling grids that usually were measured after major storms to determine peak accumulations. These experimental watersheds were often near NRCS snow courses and, in an earlier study, the snow course data from seven ponderosa pine or mixed conifer watersheds, extending from south of Flagstaff to the White Mountains and ranging in mean elevation from 2,120 to 2,765 m (6,950 to 9,069 feet), were evaluated for their applicability to determine snow conditions, primarily snow water equivalents, on the experimental areas (Gottfried and Ffolliott 1981). The analyses showed that although there were differences in water equivalent measurements between NRCS and watershed snow data from a paired site, significant linear relationships existed between them. It was determined, therefore, that the snow course data could be used to describe snow conditions on adjacent watersheds. The relationship between the East Fork of Willow Creek and the Hannagan Meadows snow courses was evaluated in the 1981 analysis.

Studies were established in the Sierra Ancha Mountains in the 1930s to investigate the interrelated influences of climate and soils, topography and geology, and the effects of watershed vegetation on stream flow, soil erosion, floods, and sedimentation (Rich and Gottfried 1976, Gottfried et al. 1999, Gottfried et al. 2002). Runoff and vegetation on the three forested Workman Creek watersheds were monitored to evaluate the impacts of several experimental and management treatments on the hydrology, sediment dynamics, and forest and forage resources. Unfortunately, intensive snow measurements and research studies on snowpack dynamics were not initiated at Workman Creek because of the isolated location. The NRCS data were not included in the previous analysis (Gottfried and Ffolliott 1981) nor used to interpret results from the watershed experiments at Workman Creek.

METHODS

Field Procedures

Snowpack water equivalent (SWE) and depth data were collected with a federal snow sample tube on the NRCS snow courses. SNOTEL data are not used since collections began at the end of the study period. The NRCS conducts snow surveys every two weeks from January 15 through April 1. Additional surveys are made earlier or later if snowpack conditions warrant them. The typical snow course contains 5 to10 measurement points spaced at 7.6 to 15.2 m (25 to 50 ft) intervals along a transect line. Although peak accumulations could occur between measurement dates or a snowpack could melt and re-accumulate between dates, the NRCS data provide good indications of peak snowpack conditions because of frequent sampling.

Analytical Procedures

The analyses for Workman Creek are based on the NRCS snow course and Rocky Mountain Research Station streamflow data from 1953 through 1979. The analysis for the Main Dam utilized all 27 years of data, while the analysis for the Middle Fork flume utilized 21 years of data, from water years 1953 through 1979; water years 1954 and 1958 were not included because of incomplete data, and the flume was not in operation from water year 1973 through 1976 (Gottfried et al. 2002). Data from the North and South Forks were analyzed to determine if the NRCS data also could be used to evaluate changes on these watersheds since the fire. Only data for the 13 years between the last treatments and 1979 were used because changes resulting from the earlier treatments might confound the analysis.

Peak snow water equivalent (SWE) data for the snow courses were obtained from a summary of SCS snow survey records (Jones 1981). This publication also provides snow depth and dates of peak accumulation information. Since the snow course is no longer measured by the NRCS, an analysis was conducted to confirm that SNOTEL and snow course peak snow water equivalent data were similar (Gottfried et al. 2002). Nine pairs of annual peak or high SWE measurements from 1981 through 1989 were compared. The analyses confirmed that SNOTEL data could be used as a proxy for snow course data for future analyses. If a longer series of SNOTEL data is needed, SNOTEL values for previous years can be estimated by the regression that has been forced through zero:

$$\text{SNOTEL} = 0.44 * (\text{Snow Course})**1.37$$

The regression has a coefficient of determination (r^2) of 0.94 and a standard error of 34.04 mm (1.34 in). The regression coefficients are based on English units. This relationship is specific to the Workman Creek situation, and may be of limited usefulness in other locations. Individual analyses should be conducted to extend the data at other locations where SNOTEL installations have replaced snow courses.

Streamflow data were obtained from the records on file with the Rocky Mountain Research Station, Flagstaff, Arizona. Snowmelt runoff quantities started from the estimated date of peak water equivalent accumulation through June 30. This period includes the runoff months of April and May and all or a part of February and March, depending on when peak occurs. June was included because baseflow from the deep soils on the watersheds is primarily derived from snowmelt, although some early summer rain events can occur. Occasionally, peak streamflows occurred before peak SWE was measured; rain-on-snow events or rain during unusually warm weather have contributed to some large peaks. Snowpacks tend to fluctuate more at mid-elevation sites, such as Workman Creek, than at higher elevations and often will be intermittent through a winter. The mean daily streamflow rate in cubic feet per second (ft^3/sec) for the day with the highest flow was determined from the records. Short duration high peaks on days of low flows were not considered. Calculations for the snowmelt period included runoff efficiency, which is defined as the proportion of runoff relative to peak water equivalent (Solomon et al. 1975). Efficiency is related to a number of factors, including antecedent soil water, soil depth, temperature, precipitation patterns, and the pathways that snowmelt takes before it enters the main channels. Efficiency appears to be independent of snow water equivalents.

Regression analyses were used to evaluate the relationships between snowmelt runoff parameters and peak snow water equivalents. Several regression models, including multiple regressions, were evaluated, but the linear regression model gave similar or better results than the other models. Data were checked for outliers and normality by standard procedures. A Type I error of $\alpha = 0.05$ was adopted for interpretation of statistical significance, and adjusted coefficients of determination (r^2) values were used to indicate how well a regression fits the data. All of the regression relationships presented in the paper are based on English units. Since vegetation manipulations on North Fork and South Fork during the 27 years influenced runoff measured at Main Dam, multiple regressions were calculated to determine if time influenced the relationships with snow water equivalents. A time factor representing the number of years since the start of the data set or an interaction value of time and snow water equivalent, following the procedure discussed by Baker (1986), were evaluated. However, the time factors were not significant in the Workman Creek or Willow Creek analyses. Means generally are presented with standard errors.

The same types of analyses were conducted on the data from the Hannagan Meadows NRCS snow course and from runoff data for East Fork of Willow Creek that are on file at the Rocky Mountain Research Station in Flagstaff. The relationship between the Willow Creek East Fork and Hannagan Meadows snow course data were re-evaluated in 1997 before conducting an evaluation of high-elevation snow water equivalent-snowmelt runoff or mean peak flow analyses (Gottfried et al. 1997). The re-analysis of the data set with additional data collected since 1980 indicated that there still was good agreement between the two sites with an r^2 of 0.91. The 22-year period from 1973, when harvesting was completed, until 1994, was used in the evaluation. A significant statistical relationship was confirmed between the Hannagan Meadows snow course and SNOTEL data.

THE WATERSHEDS

Workman Creek

The Workman Creek watersheds are part of the Sierra Ancha Experimental Forest, which is located within the Salt River drainage, about 48 km (30 mi) north of Globe, on the Tonto National Forest. The three watersheds--North Fork (100.4 ha (248 ac)), Middle Fork (210.8 ha (521 ac)), and South Fork (128.7 ha (318 ac))--were instrumented in 1938 to study the hydrology of mixed conifer forests and to determine changes in streamflow and sedimentation as a result of manipulating the forest vegetation (Rich and Gottfried 1976). The area is between 2,009 and 2,354 m (6,590 and 7,724 ft) in elevation. The NRCS snow course received an average of about 920 mm (36.2 in) of annual precipitation between 1960 and 1991 (Martinez 1993); two-thirds of the annual precipitation falls during the October through May period, mostly as snow, although heavy winter rain or rain-on-snow events occur, and the remainder comes during the summer monsoon period. The three wettest months are December, March, and January and the driest months are May and June. The undisturbed forest cover consisted of ponderosa pine (*Pinus ponderosa*), Rocky Mountain Douglas-fir (*Pseudotsuga menziesii* var. *glauca*), and white fir (*Abies concolor*), with minor amounts of aspen (*Populus tremuloides*) and Gambel oak (*Quercus gambelii*). New Mexican locust (*Robinia neomexicana*) was a prevalent understory species. The Middle Fork supported a dense stand of mixed conifer and ponderosa pine that averaged more than 45.9 m^2 /ha (200 ft^2 /ac) of basal area.

Perennial streamflow was recorded continuously at 90° V-notch weirs at North Fork and South Fork and a combination 90° V-notch weir and 2.4 m (7-ft)-Cipolletti weir at Main Dam below the confluence of the three catchments. The Main Dam measures streamflow from the entire 439.9 ha (1,087 ac) watershed. The differences between Main Dam and the other two stations determined Middle Fork runoff. Prior to treatments, average annual runoff ranged from 86.6 ± 11.9 mm (3.41 ± 0.47 in) at South Fork to 81.3 ± 20.8 mm (3.20 ± 0.82 in) at Middle Fork. A 0.9 m (3-ft) trapezoidal flume was constructed below the main 166.3 ha (411-ac) section of Middle Fork in July 1952, near its confluence with South Fork and North Fork. The flume was operated from water year 1953 through 1972 and from 1977 through 1983. A water year is the period from October 1 through September 30. A weather station that was located in Peterson's Meadow to the north of the NRCS snow course was reestablished in June 2000 after the Coon Creek Fire.

Past Treatments and Results

A brief review of the past treatments and results of watershed research at Workman Creek are helpful in placing this study into perspective. One objective for developing the snowpack-runoff relationships between the NRCS and Workman Creek data is to provide a basis for interpreting the impacts of previous experimental treatments on streamflow parameters, especially for the period when the installations were deactivated. The different treatments also are affecting current streamflow.

North Fork: The objective on North Fork was to determine the potential of increasing water yields by removing the forest and converting to a grass cover in a series of steps (Rich and Gottfried 1976, Gottfried et al. 1999). The treatments were experimental and selected to cover a range of possible manipulations. The first treatment was implemented in 1953 when riparian trees, such as Arizona alder (*Alnus oblongifolia*) and bigtooth maple (*Acer grandidentatum*), were cut along the stream channels. The next treatment, in 1958, converted the moist-site forest vegetation, mostly Douglas-fir and white fir, to grass on about 32.4 ha (80 ac) nearest the channel. Large trees were harvested and smaller trees and unmerchantable material was windrowed and burned. Cleared areas were seeded with grass species. The final treatment, in late 1966, was the harvesting of the dry-site forest, primarily ponderosa pine, on 40.5 ha (100 ac). A prescribed fire was used to remove residual trees, and the area was seeded with grasses. Locust and Gambel oak became established on many sites within the watershed.

Streamflow increased significantly ($\alpha = 0.05$) from both the moist- and dry-site treatments, but not from the 1953 riparian treatment. The moist-site treatment resulted in an increase of 42 ± 10% or 32.0 ± 7.4 mm (1.26 ± 0.29 in) and the dry-site treatment resulted in an increase of 31 ± 9% or 33.5 ± 9.4 mm (1.32 ± 0.37 in) (Rich and Gottfried 1976). The combined effect was an increase of 84 ± 11% or 68.6 ± 8.9 mm (2.70 ± 0.35 in). Hibbert and Gottfried (1987) determined that the increases remained stable for 13 years following treatment. The Coon Creek Fire resulted in low to moderate burn severities on North Fork, although some of the forested areas had high burn severities.

South Fork: The first treatment on South Fork was designed to test a common forest management prescription for the time. The watershed was harvested in 1953 according to a standard single-tree selection prescription. In 1957, a wildfire burned 24.3 ha (60 ac) near the top of the watershed. A total of 45% of the original basal area on South Fork was removed in these two events. The objective of the second treatment, in late 1966, was to convert the mixed conifer vegetation to a pure ponderosa pine stand by removing other tree species and planting pine seedlings. Larger trees of all species were harvested and residual pine stands were thinned. The residual ponderosa pine stands were to be maintained at 9.2 m^2 /ha (40 ft^2/ac) to determine if this density would optimize both timber and water production.

The single-tree selection method produced a small but significant increase in runoff, about 7 ± 6% or 5.8 ± 5.1 mm (0.23 ± 0.20 in). The results of the attempted conversion to a pure ponderosa pine stand were similar to the water yield increases from North Fork. The increase was 111 ± 16% or 93.2 ± 13.2 mm (3.67 ± 0.52 in) (Rich and Gottfried 1976). The increases were sustained during the 13 years used in the last data analysis (Hibbert and Gottfried 1987). The watershed currently contains a mixture of ponderosa pine small sawtimber, poles, and seedlings, and locust and oak trees. Burn severities caused by the Coon Creek Fire were low to moderate, although some planted ponderosa pine stands were destroyed.

Middle Fork: Middle Fork was reserved as the control watershed, since the standard paired watershed design was being used to quantify changes in streamflow related to treatments on the other two watersheds (Gottfried et al. 1999). The Middle Fork was severely burned in the Coon Creek Fire. A post-fire survey indicated that most of the trees had been killed or severely damaged and that the duff layer and most slash had been consumed.

Implications of Past Research

The Workman Creek experiments bracketed the water yield increases possible through a range of vegetation treatments. Increases were achieved by replacing deep-rooted trees with shallower-rooted grasses, shrubs, and tree seedlings that utilized less water. Less water was withdrawn and less precipitation was needed to recharge the soil resulting in an earlier and more efficient movement of water into the stream channels. While many of these treatments would not be considered for present day management, the results from Workman Creek provided guidance for subsequent watershed research that evaluated multiresource prescriptions, which removed fewer trees or created smaller openings, and provided managers and researchers with information about the implications of management on the water resources (Gottfried et al. 1999).

East Fork of Willow Creek

The East Fork of Willow Creek is located within the Apache-Sitgreaves National Forests in east-central Arizona, south of Alpine. Hydrological and other research measurements began on East Fork and the adjacent West Fork in late 1962. Elevations on the 197.9-ha (489-ac) watershed range from 2,682 to 2,835 m (8,800 to 9,300 ft) and slopes average about 20% (Gottfried 1983). The soil is a stony, silty clay loam derived from basalt parent material. The watersheds received an average (with standard deviation) of 873.8 ± 193.0 mm (34.4 ± 7.6 in) of annual precipitation over the 32 years of record. The watershed originally supported an old-growth, uneven-aged southwestern mixed conifer stand consisting of Rocky Mountain Douglas-fir, white fir, ponderosa pine, southwestern white pine (*P. strobiformis*), Engelmann spruce (*Picea engelmannii*), blue spruce (*P. pungens*), corkbark fir (*A. bicolor*), and quaking aspen. An average acre contained 983 trees/ha (398 trees/ac), and 44.3 m^2 /ha (193 ft^2 /ac) (Gottfried 1983). A 9.7 ha (24 ac) meadow occurs adjacent to the channel in the lower part of the watershed.

In 1972, the East Fork was harvested as part of a watershed management experiment designed to test the effects of the best mixed conifer forest management practices of the 1970s on water, timber, and wildlife resource values (Gottfried 1983). Approximately 121.4 ha (300 ac) were harvested according to a diameter-limit prescription and 45.7 ha (113 ac) were harvested according to a selection prescription. Other areas either were not harvested or received other treatments. The diameter-limit treatment and subsequent wind damage resulted in heavy reduction in stand conditions within that unit; about 68% of the trees and 82% of the basal area were removed in the harvesting and later salvage operations. Aspen initially became the dominant overstory species here, and in 1978, also accounted for 69% of the seedlings, saplings, and small poles. Changes in the selection area were more modest with reductions of 35% in number of trees and 29% in basal area. The treatment resulted in a 54% increase in water yields or 96.0 mm (3.78 in) (Gottfried 1983).

RESULTS AND DISCUSSION

Workman Creek

Precipitation and Runoff

The 27-year study period included some of the wettest and driest years that have been measured at Workman Creek. The average date of peak snowpack accumulation between 1953 and 1979 was February 15, when an average of 132.1 ± 20.3 mm (5.2 ± 0.8 in) of water were measured; however, the peak occurred on January 15 in six years and on April 1 in one year (1979). The greatest peak snow water equivalent (510 mm (20.1 in)) occurred on March 15, 1973 while the smallest (30.5 mm (1.2 in)) occurred on January 15, 1972. Snow was measured on every early February visit, while the snow course was bare during 56% of the early April visits. Annual runoff averaged 117.1 ± 22.4 mm (4.61 ± 0.88 in) for Main Dam (1953-1979) and averaged 70.4 ± 18.5 mm (2.77 ± 0.73 in) at the Middle Fork flume for the period of record being evaluated.

Snowmelt Runoff and Peak Snow Water Equivalent

Main Dam: A linear relationship was developed between snowmelt runoff and peak snow water equivalent (Table 1) (Gottfried et al. 2002). Peak snow water equivalent averaged 177.3 ± 24.6 mm (6.98 ± 0.97 in) during the period, while snowmelt runoff averaged 50.0 ± 8.6 mm (1.97 ± 0.34 in). The highest runoff was in 1973 with 233.4 mm (9.19 in) and the lowest year was 1955 with 8.1 mm (0.32 in). Annual precipitation in 1973, 1,546.9 mm (60.9 in), was the highest year on record. Snowmelt runoff accounted for 51 % of the 457.2 mm (18.0 in) annual runoff from the three Workman Creek watersheds in 1973.

Middle Fork Flume: A linear regression also was defined for the relationship between snowmelt runoff and peak snow water equivalents (Table 1). The highest value on record was 193.6 mm (7.62 in) in 1968; and the lowest year was 0.8 mm (0.03 in) in 1972. The flume was closed in 1973. The relatively high r^2 for the flume could be partially related to the fact that the Workman Creek snow course is within that watershed.

North Fork and South Fork: The relationships between peak snow water equivalent and snowmelt runoff for both watersheds for the 13-year post treatment periods were significant (Table 1). If future snow accumulations at the NRCS site are unaffected by the fire, these equations could be used to determine cumulative changes related to vegetation growth and the fire on the two watersheds. Snowmelt runoff values for the missing years could be calculated if the post-fire relationships were similar to those for the 13-year treatment periods.

Peak Mean Daily Runoff and Peak Snow Water Equivalent

Main Dam: _A significant linear relationship did not exist between mean streamflow rates for the day of highest yearly snowmelt runoff and peak snow water equivalent at the Workman Creek snow course (Gottfried et al. 2002). This result was primarily attributed to the peak flow of over 1,387.5 L/s (49 cfs) in 1954 when only 116.8 mm (4.6 in) of peak snow water equivalent were measured. The peak occurred during a storm period that extended from March 21 through 26 and produced 274.3 mm (10.8 in) of precipitation. The snow course was bare on March 15 and contained 30.5 mm (1.2 in) of snow water equivalent on April 1. The storm period was followed by very warm temperatures that melted much of the snow (T. Pagano, personal correspondence, June 2003); some of the ablation also could have been related to rain-on-snow or a rain events. If the 1954 record is removed from the analysis, a significant relationship can be developed (Table 1). Peak daily snowmelt flow is significantly related to snowmelt runoff volume when the 1954 data are not included. The regression has an adjusted r^2 of 0.74 and a standard error of 60.6 L/s (2.14 cfs). The average peak flow for the day of greatest runoff, excluding 1954, was

127.7 ± 23.2 L/s (4.51 ± 0.82 cfs); the highest value was 456.5 (16.12 cfs) in 1973 when 510.5 mm (20.1 in) of water were measured in 1,524.0 mm (60.0 in) of snow depth. The lowest flow was 9.6 L/s (0.34 cfs) in 1972 when the snow survey indicated 30.5 mm (1.2 in) of water in 101.6 mm (4 in) of snow depth on January 15. During the 27 years of record, two peak days were in January, five in February, 13 were in March, and seven were in April. Future analyses might be useful to evaluate the relationships among peak flows, snow water equivalent, solar radiation, and temperatures and the role of antecedent soil conditions.

Table 1. — Significant Regressions Between Snowmelt Runoff (Runoff) or Mean Peak Flows (Peak) and Snow Water Equivalents (SWE) at Workman Creek and the East Fork of Willow Creek. The regressions were calculated and are presented using inches for Runoff and SWE and cubic feet per second for Peak.

Snowmelt Runoff

Watershed	Regression	Adjusted r^2	Standard Error
Main Dam	Runoff = 0.12 +0.26 (SWE)	0.54	1.22
Middle Fork Flume	Runoff = -0.71 + 0.31 (SWE)	0.70	0.96
North Fork (1967-1979)	Runoff = 0.34 + 0.35 (SWE)	0.77	1.16
South Fork (1967-1979)	Runoff = 0.58 + 0.45 (SWE)	0.77	1.50
Willow Creek	Runoff = -0.94 + 0.71 (SWE)	0.87	1.97

Peak Mean Daily Runoff

Watershed	Regression	Adjusted r^2	Standard Error
Main Dam (wo/ 1954)	Peak = 0.75 + 0.53 (SWE)	0.40	3.22
Middle Fork Flume	Peak = -0.60 + 0.32 (SWE)	0.62	1.17
North Fork (1967-1979)	Peak = 0.05 + 0.23 (SWE)	0.62	1.06
South Fork (1967-1979)	Peak = -0.78 + 0.44 (SWE)	0.54	2.39
Willow Creek	Peak = -0.07 + 0.48 (SWE)	0.72	2.09

Middle Fork Flume: A regression relationship was calculated between peak snow water equivalent and the peak flows at the Middle Fork Flume (Table 1). The mean was 41.9 ± 11.9 L/s (1.48 ± 0.42 cfs) and the values ranged from 207.6 L/s (7.33 cfs) in 1968 to 0.8 L/s (0.03 cfs) in 1972. The earliest peak flow was on January 12 and the latest peak was on April 17; three peak days during the analysis period were in January, five in February, nine in March, and four in April.

North and South Forks: Regression relationships were developed between peak mean daily flows and snow water equivalent for the treated watersheds for the 1967 through 1979 water years (Table 1).

Runoff Efficiency

Main Dam: Runoff efficiency is related to antecedent soil water, soil depth, temperature, and precipitation, patterns; it appears independent of snow water equivalent. The pathway that snowmelt takes to reach the channel system also influences efficiency. Significant regressions were not developed between maximum snow water equivalents and runoff efficiency. The average efficiency was 32.6 ± 4.5%. Efficiencies ranged from 6.6 to 117.1%; the highest reading of over 100% in March 1970, could be related to a rain event, since 160.0 mm (6.3 in) of moisture were measured that month. The peak snowpack in 1970 was measured in January.

The Middle Fork Flume: A significant relationship could not be developed for efficiency measured at the flume. The mean was 16.6 ± 2.6%, and the range was from 1.3 to 40.5%. The runoff efficiency in 1970 was 38.1%.

East Fork of Willow Creek

Precipitation and Runoff

The 22-year study period included some of the wettest years on record. Average annual precipitation (with standard deviation) at Willow Creek was 932.2 ± 203.2 mm (36.7 ± 8.0 in); totals for six of the years were greater than one standard deviation above the long-term mean and only two years were one standard deviation below the mean (Gottfried et al. 1997). The NRCS Hannagan Meadows snow course is located approximately 2.0 km (1.25 mi) to the southeast of the approximate center of Willow Creek East Fork (Gottfried and Ffolliott 1981). The course, which was first measured during the winter of 1963-64, is at 2,771 m (9,090 ft) in elevation and is surrounded by a mixed conifer forest. A SNOTEL station was established in 1981. Average snow water equivalents were relatively high during the period. The average date of peak snowpack accumulation was about March 15 with the earliest date occurring on January 30, 1989, one of the drier years, and the latest peaks occurring around April 1 for several of the wetter years. The greatest peak snow water equivalent (685.8 mm (27.0 in)) occurred on February 25, 1993 while the smallest was 111.8 mm (4.4 in) on March 14, 1986. Streamflow measurements at Willow Creek are made at a 120° V-notch weir. Annual runoff averaged 289.0 ± 37.1 mm (11.38 ± 1.46 in) for the period, with most runoff occurring during April and May.

Snowmelt Runoff and Peak Snow Water Equivalent

A significant linear relationship was developed between snowmelt runoff and peak snow water equivalent (Table 1). The linear regression has an r^2 of 0.87, indicating that 87 percent of the total variation in snowmelt runoff is associated with the regression (Gottfried et al. 1997). The standard error is 50.0 mm (1.97 in). Peak water equivalents averaged 337.1 ± 37.3 mm (13.27 ± 1.47 in) during the period while snowmelt runoff averaged 216.2 ± 28.4 mm (8.51 ± 1.12 in). The highest runoff was in 1973 with 476.0 mm (18.74 in) and the lowest year was 1990 with 46.0 mm (1.81 in). Annual precipitation in 1973, 1,194.6 mm (47.03 in), was the highest on record. Snowmelt runoff accounted for an average of 75.4 ± 2.6% of the annual runoff from Willow Creek East Fork. The analysis indicated that snowmelt runoff is related to peak water equivalent.

The multiple regressions, including the time factor, indicated that hydrological conditions on the watershed had not changed over the period. This may be surprising because the overstory has been recovering since treatment (Gottfried 1983). However, the last forest inventory showed that aspen, a deciduous tree, was the main species in the overstory and that it dominated the understory. Timmer et al. (1980), working in northern Arizona, reported greater snowpack accumulations under two aspen stands than under an adjacent ponderosa pine stand. They indicated reduced interception losses as one reason for this difference. Timmer et al. (1980) determined that aspen stand densities, in terms of number of stems or basal area, were not highly correlated with water equivalent. Although this was not confirmed at Willow Creek, it would explain why changes in the aspen stand might not influence runoff. Increases in aspen tree heights could benefit snowpack accumulations by restricting wind movement across the snow surface and reducing snowpack evaporation. However, the snow hydrology of the watershed would change over time as the conifers reoccupy the overstory and suppress the aspen cover.

Peak Mean Daily Runoff and Peak Snow Water Equivalent

A significant linear relationship was developed between mean streamflow rates for the day of highest yearly snowmelt runoff and peak snowpack water equivalent measurements at Hannagan Meadows (Table 1) (Gottfried et al. 1997). The r^2 for this relationship is 0.72 and the standard error is 59.2 L/s (2.09 cfs). Average peak flow for the day of greatest runoff was 178.4 ± 23.5 L/s (6.30 ± 0.83 cfs); the highest value was 410.0 L/s (14.48 cfs) in 1973 when 553.7 mm (21.8 in) of water were measured in 1,701.8 mm (67 in) of snow depth at Hannagan Meadows. The lowest flow was 44.5 L/s (1.57 cfs) in 1990 when the snow survey indicated 165.1 mm (6.5 in) of water in 558.8 mm (22 in) of snow. Peak flow dates occurred between March 12 and April 30 with an average date of April 10.

Runoff Efficiency

A significant relationship could not be developed between peak snowpack conditions and snowmelt runoff efficiencies. Similar efficiencies of over 85% were noted for the highest and lowest snow accumulation years in the record. Average efficiency was 61.5 ± 3.5%.

WORKMAN CREEK COMPARED TO WILLOW CREEK

It is interesting for watershed managers to compare results from Workman Creek with a similar set of analyses conducted on data from the higher elevation Willow Creek East Fork and the Hannagan Meadow snow courses. Managers are concerned about the ability to predict streamflow from snowpacks in the Southwest, especially at mid-elevations where snowpacks can be ephemeral. The results show differences in snowpack behavior at the two elevations. The values for both snowmelt runoff and peak mean daily snowmelt runoff for Willow Creek were determined in the same manner as for Workman Creek. The analyses produced a linear regression for snowmelt runoff with an r^2 of 0.87 and a linear regression for peak runoff with an r^2 of 0.72. Both of the relationships explain more of the variation than do the similar relationships for Main Dam and Middle Fork Flume of Workman Creek (Table 1). One explanation for the difference is that these higher elevation sites experience less melting during the winter than do the lower elevation Workman Creek sites. Snowmelt efficiencies are influenced by several factors but they are an indicator of snowpack dynamics on the watershed. The average snowmelt efficiency at Willow Creek was 61.5 ± 3.5% compared to 32.6% for Main Dam and 16.6% for Middle Fork. Snowpack conditions at Willow Creek are less likely to fluctuate as much as the snowpack at Workman Creek, where the snowpacks are more intermittent because of warmer air temperatures and have the potential for more rain-on-snow events or rain events that would occur as snow at higher elevations. A greater percentage of the annual snow water equivalent is assumed lost to evaporation and sublimation at Workman Creek. Snowpack dynamics at Willow Creek may be more similar to conditions in more northern regions than they are to snowpacks at mid-elevation sites in the Southwest. The difference in precipitation form is probably the cause of the high peak in March 1954 and the high efficiency in 1970. The differences in precipitation form were observed during some of the warm storms that passed through Arizona during the late 1970s when it rained at Workman Creek and snowed at Willow Creek.

CONCLUSIONS

Snowpack accumulations and melt are important to the arid Southwest. Land and water managers should understand snowpack dynamics and have the abilities to predict the characteristics of snowmelt generated streamflows. Managers rely on the NRCS snow data as an index of basin conditions to regulate and allocate winter runoff in downstream areas. The NRCS information provides relative values of annual fluctuations in snow water equivalents, but actual measurements usually are not used directly to predict runoff values from small headwater areas. The current study shows that statistical relationships exist between snowmelt runoff quantities or resulting peak daily flows from small forested watersheds and peak snow water equivalent data from local NRCS stations. These relationships are useful even though the NRCS data often do not indicate actual snowpack conditions on the watershed. A NRCS site within a watershed would provide a closer value for snow conditions data, but this is not practical. The Workman Creek relationships could enable researchers and managers to ascertain the impacts of the Coon Creek Wildfire on snowmelt related hydrologic processes (Gottfried et al. 2002). The use of statistically similar relationships between the last treatment period and the post-fire period on the North Fork and South Fork provides a method of estimating winter streamflows for the years when the installations were closed.

The comparisons among the Workman Creek watersheds and Willow Creek demonstrate the differences in snowmelt runoff and mean peak flows from mid-elevation and high elevation watersheds. The statistical relationships at Willow Creek explained more of the variation than did similar regressions for Workman Creek. The snowmelt efficiencies at Willow Creek, which averaged 61.5 %, were greater than at the Main Dam or Middle Fork Flume of the Workman Creek. These findings are likely related to the small amount of overall melting occurring in the higher elevations over the winter period. The snowpacks are generally not intermittent, except in years of low precipitation, and basically accumulate snow water throughout the winter, and releasing it in the spring. The snowpack is less likely to be affected by rain-on-snow events that can result in rapid melt or by relatively high temperatures that cause water losses through melting and sublimation.

The problem of relating streamflow to the fluctuating and often ephemeral snowpacks at mid-elevation sites has been recognized by the NRCS (T. Pagano, personal correspondence, June 2003). Arizona is one of the few states where mid-month surveys are conducted; only one monthly survey is sufficient in more northern regions. However, even the increased survey intensity can miss snowpack fluctuations and related streamflow events, such as occurred during and after the storm period of March 1954. The problem may be less of a concern at present since SNOTEL installations have the capability to provide daily snowpack and meteorological information.

An examination of other NRCS-watershed data could confirm the basic form of these relationships and possibly allow their extrapolation to similar adjacent un-gauged watersheds. Land managers could use this information to determine the effects of snowmelt runoff on stream channels, riparian vegetation, fishery resources, and status of mountain lakes and ponds. These data also could be used in the development or testing of computer simulation models designed for predicting runoff from headwater watersheds.

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