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Authors: Ffolliott, Peter F., and Gottfried, Gerald J.

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# MAGNITUDES AND TIMING OF SEASONAL PEAK SNOWPACK WATER EQUIVALENTS IN ARIZONA: A PRELIMINARY STUDY OF THE POSSIBLE EFFECTS OF RECENT CLIMATIC CHANGE

PETER F. FFOLLIOTT, School of Natural Resources and the Environment, University of Arizona, Tucson, AZ 85721 and

GERALD J. GOTTFRIED, Rocky Mountain Research Station, Tonto National Forest, 2324 E. McDowell Rd, Phoenix, AZ 85006

## ABSTRACT

Field measurements and computer-based predictions suggest that the magnitudes of seasonal peak snowpack water equivalents are becoming less and the timing of these peaks is occurring earlier in the snowmelt-runoff season of the western United States. These changes in peak snowpack conditions have often been attributed to a warming of the regional climate. To determine if these changes are also occurring in Arizona, almost 75 years of water equivalent measurements on snow courses maintained by the U.S. Natural Resources Conservation Service and their cooperators have been analyzed in a preliminary study of possible effects of recent climatic change. The results of this analysis agree generally with the findings of other studies in the Western states.

## INTRODUCTION

Field measurements and computer-based predictions indicate that the magnitudes and timing of seasonal peak snowpack water equivalents are changing in the western United States, with the magnitudes becoming less and the timing occurring earlier in the snowmelt-runoff season (Mote et al. 2005, Snyder and Sloan 2005). These changes in peak snowpack conditions have often been attributed to a warming of the regional climate. Because snowmelt-runoff is a major source of water flowing into central Arizona's reservoir systems (Ffolliott and Baker 2000, Baker and Ffolliott 2003), a preliminary study of the long-term magnitudes and timing of seasonal peak snowpack water equivalents was undertaken to determine if the reported changes in snowpack conditions are also occurring in this state. The data analyzed were almost 75 years of snowpack water equivalent measurements obtained on a network of courses maintained by the U.S. Natural Resources Conservation Service (formerly the U.S. Soil Conservation Service) and their cooperators. These courses have been established in the major river basins of Arizona including the Gila, Salt, Verde, San Francisco, and Little Colorado Rivers. The measurements obtained are used primarily to develop predictions of subsequent snowmelt-runoff volumes of water. It was not necessarily the purpose of the network of course measurements to obtain estimates of the average snowpack water equivalents within the river basins.

## STUDY PROTOCOL

Water equivalents were measured originally with a snow tube on a bi-weekly basis at the beginning and mid-point of a month beginning generally in early January and continuing to the end of the snowmelt-runoff season. However, this bi-monthly schedule could not always be adhered to because unfavorable weather conditions prevented travel to the courses or the lack of available personnel to measure snowpacks on the courses. Measurements of water equivalents obtained with a snow tube have been replaced in recent years by transmitting snowpack water equivalents sensed on pressure pillows located on selected courses to a central processing facility as part of the Snow Data Telemetry (SNOWTEL) System. Data available in SNOWTEL represent the "real-time conditions" on a course and, importantly, are readily accessible at almost any time. To be consistent with the earlier bi-weekly measurements with a snow tube, the water equivalent measurements sensed on the pressure pillows at the beginning and mid-point of a month were the basis for analyzing the SNOWTEL data in this study.

After the first snow courses in Arizona were established in the middle of the 1930s, additional courses were added to the network in the following years to improve the predictions of snowmelt-runoff volumes of water, while established courses were eliminated because they did not contribute to the statistical significance of the predictions of snowmelt-runoff volumes (Jones 1980). Therefore, the number of courses in the network has ranged from about 35 to 76 throughout the 75 years of measurements as a consequence. Water equivalent mea-

measurements on a subset of 23 to 41 of the courses with the longest continuous measurements were selected for analysis in this study. The varying number of courses in this analysis was necessitated because of the changing number of courses in the network throughout the study; the requirement that measurements of water equivalent on some of the courses to overlap to develop a continuous “timeline” for the analysis; and a lack of measurable snow on some of the courses in some of the years.

The magnitudes and occurrences of the seasonal peak snowpack water equivalents on these courses were averaged for 10-year intervals for the analysis purposes. There were less than 10 years of measurement in the decade of the 1930s, however, because the first snow courses in Arizona were established in the middle of the 1930s. Otherwise, the 10-year intervals encompassed the averages of the measurements obtained in 1940 to 1949, 1950 to 1959, and so on.

The results of this study should be interpreted within the context of the locations selected for establishing the snow courses. Because the network of snow courses was established primarily to provide an index to predict subsequent snowmelt-runoff volumes of water, the courses were located on sites where a measurable snowpack was likely to

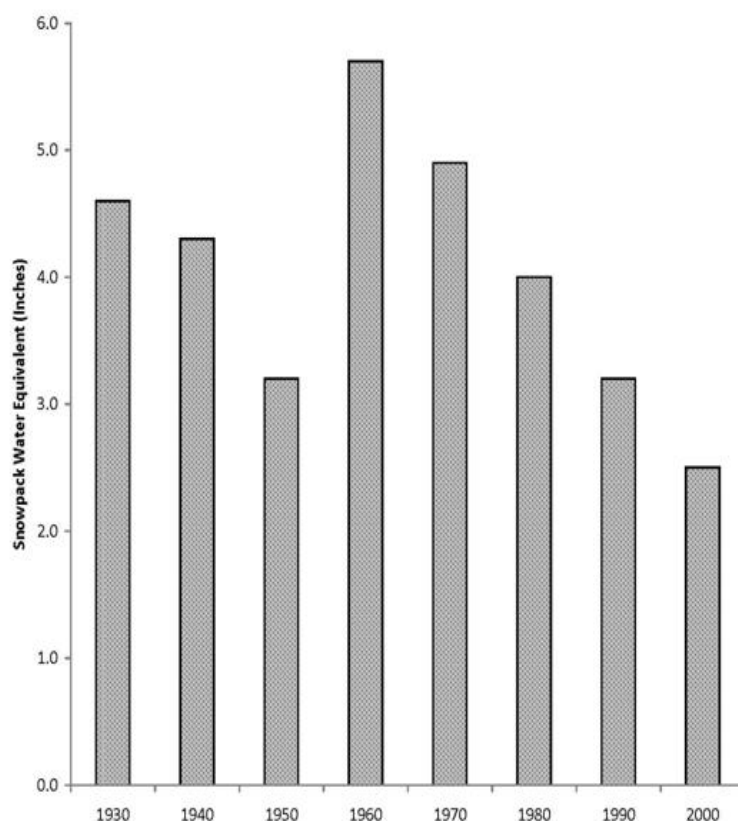
persist throughout the snowfall season. A prediction of snowmelt-runoff volumes from the measurements on a course was not possible if a measurable snowpack was absent on the course. The courses were also located in readily accessible areas to obtain timely water equivalent measurements when a snow tube was the basis of the measurements and on sites that were protected (to the extent possible) from prevailing winds to minimize the blowing of snow onto and off of the course.

The differing snowpack measurement methods, sampling procedures, and timelines of the measurements throughout the study precluded a rigorous statistical analysis of the data sets. Therefore, only general findings of the study are presented here.

## RESULTS AND DISCUSSION

### Magnitudes of Seasonal Peak Snowpack Water Equivalents

Varying magnitudes of peak seasonal snowpack water equivalents occurred on the courses in the decades prior to the 1950s as illustrated in Figure 1. This variability was likely indicative of the “inherent variability” in peak snowpack conditions before the possible climatic changes in the recent decades.



**Figure 1.** Magnitudes of seasonal peak snowpack water equivalents on the network of snow courses maintained by the U.S. Natural Resources Conservation Service. Average water equivalents for the decades of the 1930s to 2000s are shown. Less than 10 years of snowpack measurements were obtained in the 1930s.

While some courses attained seasonal peaks on a particular date, other courses reached this condition either before or after that date, with the seasonal peak in the network reflecting this variability.

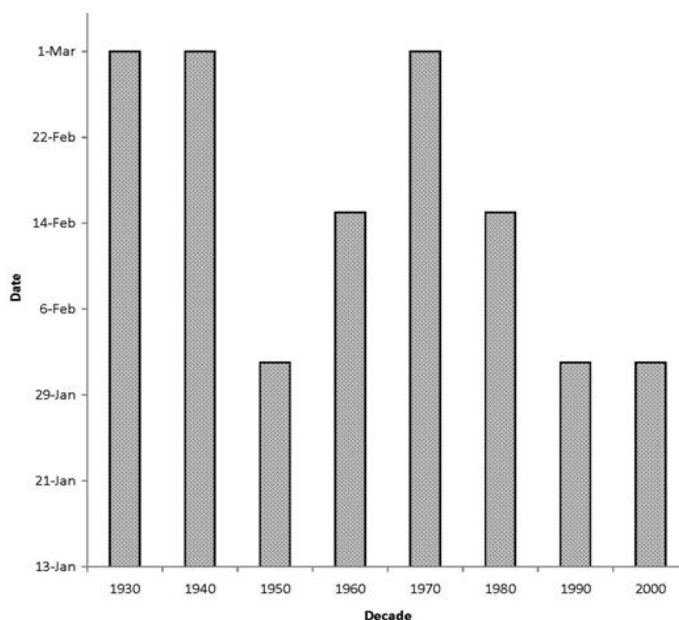
The decline in the magnitudes of seasonal peak snowpack water equivalents in the 1950s coincided with a prolonged drought in the state at this time (Sellers et al. 1987). This drought was followed by above average snowfall amounts in the 1960s that are shown by the comparatively high magnitude of the average of the seasonal peak snowpack water equivalents in this decade (Fig. 1). A steady decline in the magnitudes of seasonal peaks averaging 0.80 to 0.85 inches per decade from the 1960s through the decade of the 2000s was then observed. This decline of 50 to 55% in the seasonal peaks in these decades was similar to that reported in other western states for the same general time period (Mote et al. 2005).

The decline in seasonal peak snowpack water equivalents from the 1960s was attributed empirically to a combination of the progressively lower annual snowfall amounts in the state and a general increase in the low winter temperatures of 0.8 to 1.4 °C since the 1960s (unpublished analysis by the authors). Neither high winter temperatures nor average winter temperatures were related to the decline in seasonal peak snowpack water equivalents in this period. It should be noted, however, that there is an inherently “high level” of spatial and temporal variability in winter temperatures throughout the state (Sellers et al. 1987, Sellers 2008).

## Timing of Seasonal Peak Snowpack Water Equivalents

Seasonal peak snowpack water equivalents appear to have occurred earlier in a season since the 1970s as suggested in Figure 2. However, this trend in timing of the peaks was “less clearly defined” than the decline in the magnitudes of the water equivalents of the peaks. The occurrence of the seasonal peak in the decade of the 1980s was similar to that in the 1960s, the latter representing a decade of above average snowfall amounts. Also, while the seasonal peaks were earlier in the decades of the 1990s and 2000s than in the 1980s, their occurrences were similar to the seasonal peak observed in 1950s, the decade of the prolonged drought in the state. That the timing of the seasonal peaks in snowpack water equivalents is occurring earlier in the season, therefore, is deemed inconclusive by the authors.

Knowing the character of the snowpack conditions in Arizona might be helpful in placing the findings of this study into the proper context. In comparison to snowpack conditions in the more northerly latitudes of the western states, snowpacks in the state are mostly intermittent, with alternating cycles of snowpack buildup followed by a depletion of the snowpack between snowfall events in a season (Ffolliott and Baker 2000). The snowpacks are also “relatively shallow” in relation to the snowpacks in other western states. The accumulated snowpack following a “normal” snowfall event in a season often averages between 2.5 and 3.5 inches in



**Figure 2.** Approximate timing of seasonal peak snowpack water equivalents on the network of snow courses maintained by the U.S. Natural Resources Conservation Service. Average dates of these seasonal peaks for the decades of the 1930s to 2000s are shown. Less than 10 years of snowpack measurements were obtained in the 1930s.

water equivalent. However, deeper accumulations of snow can be found on sites to the leeward side of a “barrier” to the prevailing north-westwardly to south-eastwardly track of the winter snowstorms, such as the opening adjacent to the edge of a dense forest overstory. Furthermore, as already mentioned, seasonal peak snowpack water equivalents on the network of courses generally occur at different times in a season in response to the varying elevational and closely related temperature gradients in the network (Beschta 1976, Sellers et al. 1987, Sellers 2008). It is possible, therefore, that the variable timing of seasonal peak snowpack water equivalents observed in this study was reflected this inherent variability.

## CONCLUSIONS

The findings presented in this paper agree generally with the results of other studies in the western states in reporting a decline in the magnitudes of seasonal peak snowpack water equivalents in recent years. The decline in water equivalents in Arizona parallels the often historically low storage of water in the downstream reservoir systems at the end of the snowmelt-runoff seasons in recent years. These seasonal peaks also appear to be occurring earlier since the 1970s, although this trend was not as clearly defined as that shown by the decline in the magnitudes of these peaks. Whether the changes reported in this study will continue into the future is unknown as they are linked intrinsically to the unpredictability of future climatic conditions. Some investigators (e.g., Kerr 2009) have suggested that a decade-long stagnation in global warming has occurred since the late 1990s. However, many of these same investigators also believe that this pause in global warming is only temporary. They argue that a “natural swing” in climatic conditions to the cool side has been holding greenhouse gasses back and such swings in climatic conditions do not last forever. Further monitoring of the snowpack conditions in Arizona will be necessary, therefore, to place the findings of this study in perspective.

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