International Symposium on
Hydrology of Mountainous Areas
Shimla (INDIA) May 28-30, 1992

Snowpack Dynamics in Mountains Area: Research Findings in The Southwestern United States

Peter F. Ffolliott

School of Renewable Natural Resources
University of Arizona
Tucson, Arizona USA

INTRODUCTION

Less than 10 percent of the annual precipitation in the southwestern United States is recovered for use by people. A large portion of the precipitation that is recovered originates on forested watersheds in mountainous areas. Even here, 80 to 90 percent of the precipitation currently is not available for downstream users. Nevertheless, part of it potentially is available. However, before more precipitation can be recovered, water yields will have to be increased.

The possibility of increasing the amount of recoverable precipitation from forested watersheds appears greater for snow than for rain. Snow accumulates on forested sites throughout the winter, providing a reservoir of water potentially available for downstream use in the spring. If snowmelt water yields were increased significantly, additional water would be available to refill reservoirs or recharge groundwater aquifers.

A review of snow research in the southwestern United States over the past 25 years is presented to describe some of the possibilities for increasing snowmelt water yields. In large part, these research efforts have been aimed at the development of snow management guidelines for increasing the amount of recoverable water derived from snowpacks that accumulate and then melt on forested watersheds. Studies have been concerned with basic snow hydrology, forest management-snow relationships, and techniques of predicting effects of management on snowpack water yields.

FOREST MANAGEMENT ACTIVITIES

Two options and combinations of these two options generally are available to the watershed manager considering use of forest management activities in attempting to increase recoverable water yields from snow:

- Reducing forest densities by thinning practices, using various intensities and combinations of intensities.

- Removing forest overstories by clearing practices, using different arrangements, sizes, and patterns of openings.

Initial emphasis of snow research in the southwestern United States was to study effects of reducing forest densities and removing forest overstories on snowpack accumulation and melt patterns.

Reducing Forest Densities

Inventory-prediction relationships describing snowpack conditions associated with the common range of densities found in montane forests of the southwestern United States have been developed (Ffolliott and Hansen 1968, Ffolliott and Thorud 1972, Timmer et al. 1984, Warren 1974). These relationships show that snowpack water equivalents generally increase as forest densities decrease. With inventory-prediction relationships watershed hydrologists are able to prescribe forest management activities involving thinning practices to increase snowpack water equivalents on-site which are available potentially for conversion into recoverable water.

Inventory-prediction relationships can be confounded by year-to-year variations in snowfall amounts. Therefore, historical data from USDA Soil Conservation Service (SCS) snow courses were analyzed to determine whether basic relationships remain the same from year-to-year (Ffolliott, et al. 1972). Of the 18 snow courses analyzed, 12 supported the hypothesis that, with a given precipitation input, distribution of the snowpack is determined primarily by spatial arrangements of forest overstories. Total snowpack water equivalents change as a function of precipitation inputs, however, "trade-offs" between snowpack water equivalents and forest densities are unchanged in time.

To provide information for temporal assessments of snowpack conditions, studies have been conducted to evaluate the usefulness of a storage-duration index in prescribing forest management activities for water yield improvement (Ffolliott and Thorud 1973, Warren and Ffolliott 1975). Storage-duration index values were obtained by adding together snowpack water equivalent measurements on successive sampling dates (Wilm 1948). Maximum index values represented high initial storage and slow melt, and minimum index values indicated with low initial storage and rapid melt. These studies have shown maximum index values to be associated with low forest densities, cool sites, and high elevations, with low index values associated with high forest densities, warm sites, and low elevations.

Removing Forest Overstories

Work carried out in the southwestern United States indicates that openings created in forest overstories increase snowpack accumulations within the cleared areas (Ffolliott et al. 1965, Gary 1974, Hansen and Ffolliott 1968, Plasencia et al. 1984). Consequently, greater accumulations of snow can be available at these locations for conversion into recoverable water than found under an undisturbed forest canopy. However, while clearing of forest overstories has been shown to affect snowfall distribution patterns, it is not always known whether total amounts snowpack water equivalents have increased on the entire watershed.

Techniques to evaluate snowpack profiles in and adjacent to forest openings have been developed. This work led to synthesis of a two-dimensional analytical technique for estimating whether an increase or decrease in snowpack water equivalents had occurred in and adjacent to forest openings at a point-in-time (Ffolliott and Thorud 1974, Gopen 1974). "Trade-offs" between changes in snowpack water equivalents and amounts of forest overstory removed to create openings also can be identified.

A series of three-dimensional models to describe snowpack conditions in and adjacent to forest openings in a dynamic framework subsequently were structured (Ffolliott 1983). These "time-space" representations provide information that can be utilized to maximize or minimize "net" effects of forest openings on snowpack conditions. Knowledge generated by these models is helpful to watershed hydrologists in situations where increased water yields from snowpacks is a consideration.

Forest management activities involving both reducing forest densities and removing forest overstories in different vegetative cover types can affect timing of snowmelt and subsequent runoff from larger watersheds. From surveys of snow accumulation and disappearance, recommendations for management activities to affect timing of snowmelt and runoff are suggested (Gary and Coltharp 1967). If the management objective is delayed snowpack depletion at lower elevations, for example, it is desirable to favor Douglas-fir over aspen forests. At higher elevation, similarity in snowpack accumulations in spruce-fir forests and grassland types and the delay in snowpack depletion in spruce-fir forests suggests two possibilities. Management for delayed snowpack depletion and snowmelt runoff would favor spruce-fir forests, with limited thinning in old-growth stands on "warmer" sites. Management for maximum snow melt and peak runoff would indicate clearing of the forest overstory.

SNOWPACK DENSITY

Snowpack density is a useful index to the stage of "ripening" in a snowpack. In general, freshly fallen snow has a density of 0.10 gm cm^3, while denser conditions are characteristic of a snowpack undergoing metamorphosis and ripening. In a ripened snowpack, additional inputs of energy will cause the snow to melt and yield water.

Studies were conducted to evaluate the usefulness of snowpack density to index of snowpack metamorphosis and ripening in the forest types of Arizona and New Mexico (Ffolliott and Thorud 1969, Ffolliott and Thompson 1977, Ffolliott 1985, Gary 1967). These studies indicated that an average snowpack density of between 0.35 and 0.40 gm cm^3 represented ripe snowpack conditions. Higher snowpack densities occurred under sparsely stocked forest stands, suggesting that forest management activities might affect ripening of snowpacks. Unfortunately, other relationships between snowpack density and inventory-prediction variables, including potential solar radiation and elevation, were either statistically nonsignificant or of little predictive value.

PROCESS AND THEORETICAL STUDIES

Process and theoretical studies have been conducted to help watershed hydrologists to better understand relationships between snowpack conditions and forest overstories. Results from these studies assist in the interpretation and extrapolation of the results from more empirical investigations.

Process Studies

Behavior of intercepted snow in the region has been evaluated with time-lapse imagery to determine the relative significance of snowfall interception in the water budget (Tennyson et al. 1974). It appears that most of the intercepted snow reaches the ground by snowslide, wind erosion, or canopy melt and, therefore, does not represent a significant loss in terms of the water budget. Potential losses to streamflow by vaporization of canopy snow and resulting meltwater seems minimal relative to the magnitude of snow that eventually reaches snowpacks either directly or indirectly from tree canopies.

Lysimeters were installed to characterize snow melt rates, timing of melt, and in general, site differences in snowpack behavior under forest overstories. Energy budget parameters were used to estimate the magnitude of snowmelt outflows from the lysimeters. Comparisons of timing of snowmelt outflows beneath the lysimeters with fluctuations in streamflow regimes of nearby watersheds showed that outflows from the lysimeters preceded streamflows by variable, but definable time lags (Gottfried and Ffolliott 1980, Jones et al. 1976). Although based on a relatively limited sample, no significant differences were observed in snowpack water equivalents and subsequent snowmelt rates among the lysimeters on forested and open sites.

Theoretical Studies

Theoretical studies of interactions of snowpack conditions and forest overstories have been undertaken to supplement and refine information obtained from the empirical and process-oriented investigations. These theoretical studies have centered on synthesis of models to describe short-wave and long-wave solar radiation exchanges between snowpacks and forest canopies (Bohren 1973, Bohren and Thorud 1973, Bohren and Barkstrom 1974). Short-wave and long-wave radiation components to a snowpack vary, in large part, as functions of a forest canopy structure. Therefore, if models can be formulated to describe the effects of manipulating forest canopies on short-wave and long-wave solar radiation transfer, build-up and ablation of snowpacks could become more predictable.

Lack of relationship between physical properties of a snowpack and its solar albedo has been a problem in predicting snowmelt and runoff regimes. To learn more about this relationship in terms of the conditions encountered in the southwestern United States, observations were made on the relation of short-wave reflectivity of recently deposited snow to its physical properties (Bergen et al. 1983). Observed solar albedo values over a "wet" snow were compared with those estimated from measurements of surface density, air permeability, and the total-to-diffuse-flux ratio by mean of several models described in the literature and by using empirical correlations to estimate grain size. Unfortunately, results of this research suggest continued difficulty in the validation of snow albedo models with on-site measurements of snow cover.

RUNOFF EFFICIENCIES

Another important step in development of snow management guidelines for increased amounts of recoverable water involved identification of physiographical and climatological factors which affect the quantity of snowmelt and runoff. Comparable forest management activities on two sites with similar vegetative characteristics often yield different amounts of runoff, if the sites have differing slope-aspect combinations, soil characteristics, and precipitation-temperature regimes. It is desirable, therefore, for watershed hydrologists to implement water yield improvement programs on sites with the greatest water yield potential. In this case, the decision would be based, in large part, upon physiographical and climatological factors, since vegetative conditions would be the same.

One measure of the effects of physiographical and climatological factors on the amount of runoff yielded from a site is "runoff efficiency," that portion of a snowpack that is converted into recoverable surface runoff (Ffolliott and Hansen 1968, Thorud and Ffolliott 1972). Both fixed and variable factors determine runoff efficiency values. Fixed factors are slope percent, aspect, soil depth and type, and watershed configuration, while variable factors include year-to-year differences in rates of snowmelt and antecedent moisture conditions.

To develop an understanding of magnitudes and ranges of runoff efficiencies, runoff efficiency values have been determined for watersheds where snowmelt water yields are a significant contributor to annual water outputs (Solomon et al. 1975a). No distinct pattern of runoff efficiencies is apparent. It was found that runoff efficiencies vary greatly from year-to-year on a given watershed, and from watershed-to-watershed in a given year. To illustrate this point, runoff efficiencies for the period of peak seasonal snowpack accumulation to cessation of snowmelt runoff can range from 20 to 45 percent on a given watershed, depending upon amounts of snowfall and timing of snowfall events in differing years. Runoff efficiencies vary from 25 to 85 percent among watersheds in a given year, with much of this difference attributed to physiographical features.

Knowledge of runoff efficiencies is useful in predicting the amount of snowmelt runoff that originates on forested watersheds. Therefore, empirical predicting equations have been synthesized to estimate the portion of a snowpack on a watershed that is converted into runoff during the snowmelt season (Solomon et al. 1975b). Equations that predict runoff efficiency from inventory-prediction variables measured before peak seasonal snowpack accumulation, and equations to estimate runoff efficiency following the completion of runoff have been developed. The first set of equations are used to estimate proportions of snowpacks converted into runoff during a season, while the second set has utility in characterizing a watershed in terms of past runoff efficiency history and water yielding potentials.

Solutions of these equations suggest that watersheds with the greatest peak seasonal snowpack accumulations and at the highest elevations are most efficient in terms of snowmelt runoff. Consequently, management activities implemented to increase snowpack water equivalents at peak seasonal accumulation would have the greatest potentials for snowmelt water yield improvement.

On large watersheds, runoff efficiencies can be affected by the timing of runoff from different vegetative types and topographies. Greater snowpack accumulations have been observed in high elevation spruce-fir forests and grasslands as compared to low elevation Douglas-fir and aspen types (Gary and Coltharp 1967). In both elevational zones, however, snowpack water equivalents were greater on northerly aspects than on southerly aspects. From these results, management for delayed snowpack depletion and runoff would favor spruce-fir cover and limited cutting in old-growth forest stands. Conversely, management for maximum snowmelt rates and peak runoff would indicate clearcutting.

REMOTE SENSING OF SNOWPACK CONDITIONS

Although quantities of water yielded from forested watersheds vary from year to year, demands for water in the southwestern United States normally exceed supplies. To satisfy the demands for water, intensive watershed management should be practiced, requiring better inventory techniques for determining quantity and distribution of water held in snowpacks under the forest overstories. Downstream reservoir managers, although largely concerned with maximizing amounts of stored water at the end of the snowmelt runoff period, must not allow reservoirs to reach capacity too soon, since this could create flood hazards.

Intensive inventories of snowpack conditions are uneconomical. However, an alternative can be to estimate snowpack conditions indirectly from measurements obtained through remote sensing techniques. It is possible, for example, to relate peak seasonal snowpack accumulation to forest overstory and topographic attributes measured on 1:15,840 aerial photographs (Larson et al. 1974). Knowledge of peak seasonal snowpack accumulation is a key criterion to estimating potential snowmelt water yields from watersheds in the region (Ffolliott and Thorud 1972).

Measures of snowpack depletion are correlated highly with volume of snowmelt runoff. Because the snowpacks in the southwestern United States are shallow and intermittent in contrast to the conditions in most Rocky Mountain states, measures of snowpack depletion also are related to extent of snow cover. To evaluate the hypothesis that runoff can be estimated from knowledge of the extent of snow cover, measures of the extent of snow cover, obtained from satellite (LANDSAT) imagery, have been related to runoff during snowpack depletion periods (Aul and Ffolliott 1975, Ffolliott and Rasmussen 1976). Snowmelt runoff can be forecast from these relationships, using measures of the extent of snow cover from satellite imagery. These relationships consequently have been incorporated into snowmelt runoff forecasting procedures.

PREDICTION TECHNIQUES AND SIMULATION MODELS

SCS snow courses in the region are measured routinely throughout the winter months to provide an index of snowpack conditions within larger watersheds. To determine whether these measurements also could be used to predict snowpack water equivalents on a small watershed-basis, a comparative analysis between SCS data from selected snow courses and measurements of snowpack conditions on experimental watersheds was undertaken (Gottfried and Ffolliott 1981). SCS data could not be utilized directly to describe watershed situations, except when the SCS snow course had been established within the watershed in question or when the watershed was located at a higher elevation. However, highly significant relationships could be developed from the paired data. These relationships could be used to estimate snowpack water equivalents on watersheds and, as a consequence, reduce or eliminate the need for intensive surveys of snowpack conditions.

Snowpacks at a point-in-time represent integrated effects of all accumulation, redistribution, and melt processes that have taken place before the time of assessment. To better understand the complexities of these processes and to allow for the prescription of management activities to manipulate snowpack conditions, an interactive computer simulation model, called SNOW, has been developed (Ffolliott and Rasmussen 1979). While this simulation model has been structured to facilitate applications by noncomputer-oriented watershed managers at remote locations, the simulator does provide the required flexibility to quantify integration of snowpack accumulation, redistribution, and melt processes within a dynamic framework. To encourage user applications, input requirements of SNOW are generated from readily available data sets.

A modification of a snowmelt simulation model for Colorado subalpine forests (Leaf and Brink 1973) provides for modeling relatively shallow and intermittent snowpacks in the southwestern United States (Solomon et al. 1976). This modified and more generalized model, termed SNOWMELT, requires only limited knowledge of "local" watershed and snowpack parameters. The only "driving" variables required are daily values for maximum and minimum air temperatures, precipitation, and solar radiation. Verification of SNOWMELT on watersheds representing a range of conditions that are common to high elevation, forested watersheds in the region has proven satisfactory.

Solar radiation measurements, as required in SNOWMELT, are not available routinely. Therefore, a method is needed to estimate this parameter from readily available information. To this end, relationships between solar radiation components and commonly observed cloud-cover characteristics have been developed (McAda and Ffolliott 1978). These relationships have been incorporated into SNOWMELT as subroutines to index the required solar radiation variable. It has been determined that cloud observations can be used as direct inputs to predict the amount of solar radiation that impinges upon a snowpack, when actual measurements of solar radiation are not available.

A computer simulation model also has been developed for estimating impacts of management activities on water yields in snow covered areas (Larson et al. 1979, Rasmussen and Ffolliott 1981). The primary "driving" variable in this model, named YIELD, is daily precipitation. Initial values for amounts of moisture stored in the soil and for average forest density conditions also are required. Outputs are values representing daily runoff, changes in soil moisture storage, evapotranspiration, and deep seepage. YIELD has been structured in an interactive format to facilitate operation by watershed managers at remote locations, using readily available data sets.

SUMMARY

Empirical field work, related process and theoretical studies, and associated remote sensing and simulation investigations which have been undertaken in the southwestern United States over the past 25 years provide management guidelines to enhance snowmelt water yields on high elevation, forested watersheds. It seems possible that management activities can be designed to increase the amount of recoverable water derived from snowpacks on watersheds with high runoff efficiencies and, at the same time, furnish wood, forage, wildlife, and amenity values, in some optimal combination, required by the people in the region.

REFERENCES

Aul, J. S., and P. F. Ffolliott. 1975. Measuring snow cover from ERTS's imagery on the Black River Basin. Hydrology and Water Resources in Arizona and the Southwest 5:215-219.

Bergen, J. D., B. A. Hutchison, R. T. McMillen, A. D. Ozment, and G. J. Gottfried. 1983. Observations on the relation of the shortwave reflectivity of recently deposited snow to its physical properties. Journal of Climate and Applied Meteorology 22:193-200.

Bohren, C. F. 1973. Theory of radiation heat transfer between forest canopy and snowpack. Symposium on the Role of Snow and Ice on Hydrology, Banff, Alberta, Canada, pp. 165-173.

Bohren, C. F., and D. B. Thorud. 1973. Two theoretical models of radiation heat transfer between forest trees and snowpacks. Agricultural Meteorology 11:3-16.

Bohren, C. F., and B. R. Barkstrom. 1974. Theory of the optical properties of snow. Journal of Geophysical Research 79:4527-4535.

Ffolliott, P. F. 1983. Time-space effects of openings in Arizona forests on snowpacks. Hydrology and Water Resources in Arizona and the Southwest 13:17-20.

Ffolliott, P. F. 1985. Snowpack density: An index of snowpack condition. Hydrology and Water Resources in Arizona and the Southwest 15:1-6.

Ffolliott, P. F. and E. A. Hansen. 1968. Observations of snowpack accumulation, melt, and runoff on a small Arizona watershed. USDA Forest Service, Research Note RM-124, 7 p.

Ffolliott, P. F., and W. O. Rasmussen. 1976. Use of satellite data to develop snowmelt-runoff forecasts in Arizona. Hydrology and Water Resources in Arizona and the Southwest 6:149-151.

Ffolliott, P. F., and W. O. Rasmussen. 1979. An interactive model of snowpack accumulation and melt dynamics in forest conditions. Proceedings, Meeting on Modeling Snow Cover Runoff, Hanover, New Hampshire, USA, pp. 359-368.

Ffolliott, P. F., and J. R. Thompson. 1977. Snowpack density on an Arizona mixed conifer forest watershed. Hydrology and Water Resources in Arizona and the Southwest 7:227-233.

Ffolliott, P. F., and D. B. Thorud. 1969. Snowpack density, water content and runoff on a small Arizona watershed. Western Snow Conference 37:12-18.

Ffolliott, P. F., and D. B. Thorud. 1972. Use of forest attributes in snowpack inventory-prediction relationships for Arizona ponderosa pine. Journal of Soil and Water Conservation 27:109-111.

Ffolliott, P. F., and D. B. Thorud. 1973. Describing Arizona snowpacks with storage-duration index. Progressive Agriculture in Arizona 25(1):6-7.

Ffolliott, P. F., and D. B. Thorud. 1974. A technique to evaluate snowpack profiles in and adjacent to forest openings. Hydrology and Water Resources in Arizona and the Southwest 4:10-17.

Ffolliott, P. F., E. A. Hansen, and A. D. Zander. 1965. Snow in natural openings and adjacent ponderosa pine stands on the Beaver Creek watersheds. USDA Forest Service, Research Note RM-53, 8 p.

Ffolliott, P. F., D. B. Thorud, and R. W. Enz. 1972. An analysis of yearly differences in snowpack inventory-prediction relationships. Hydrology and Water Resources in Arizona and the Southwest 2:31-42.

Gary, H. L. 1967. Density variation in a snowpack of northern New Mexico. Western Snow Conference 35:6-10.

Gary, H. L. 1974. Snow accumulation and melt along borders of a strip cut in New Mexico. USDA Forest Service, Research Note RM-279, 8 p.

Gary, H. L., and G. B. Coltharp. 1967. Snow accumulation and disappearance by aspect and vegetation type in the Santa Fe Basin, New Mexico. USDA Forest Service, Research Note RM-93, 11 p.

Gopen, S. R. 1974. A time space technique to analyze snowpacks in and adjacent to openings in the forest. Master's Thesis, University of Arizona, Tucson, Arizona, 77 p.

Gottfried, G. J., and P. F. Ffolliott. 1980. An evaluation of snowmelt lysimeters in an Arizona mixed conifer stand. Hydrology and Water Resources in Arizona and the Southwest 10:221-229.

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.

Hansen, E. A., and P. F. Ffolliott. 1968. Observations of snow accumulation and melt in demonstration cuttings of ponderosa pine in central Arizona. USDA Forest Service, Research Note RM-111, 12 p.

Jones, M. E., P. F. Ffolliott, and David B. Thorud. 1976. Lysimeter snowmelt in Arizona ponderosa pine forests. Hydrology and Water Resources in Arizona and the Southwest 6:177-179.

Larson, F. R., P. F. Ffolliott, and K. E. Moessner. 1974. Using aerial measurements of forest overstory and topography to estimate peak snowpack. USDA Forest Service, Research Note RM-267, 4 p.

Larson, F. R., P. F. Ffolliott, W. O. Rasmussen, and D. R. Carder. 1979. Estimating impacts of silvicultural management practices on forest ecosystems. Proceedings of Conference on Best Management Practices for Agriculture and Silviculture, Rochester, New York, USA, pp. 281-294.

Leaf, C. F., and G. E. Brink. 1973. Computer simulation of snowmelt within a Colorado subalpine watershed. USDA Forest Service, Research Paper RM-99, 22 p.

McAda, D. P., and P. F. Ffolliott. 1978. Solar radiation as indexed by clouds for snowmelt modeling. Hydrology and Water Resources in Arizona and the Southwest 8:175-181.

Plasencia, D. J., P. F. Ffolliott, and G. J. Gottfried. 1984. Effects of mixed conifer forest openings on snow. Hydrology and Water Resources in Arizona and the Southwest 14:57-61.

Rasmussen, W. O., and P. F. Ffolliott. 1981. Prediction of water yield using satellite imagery and a snowmelt simulation model. In: Deutsch, M., D. R. Wiesnet, and A. Rango. (eds.) 1981. Satellite Hydrology. American Water Resources Association, Minneapolis, Minnesota, USA, pp. 193-196.

Solomon, R. M., P. F. Ffolliott, and D. B. Thorud. 1975a. Characterization of snowmelt runoff efficiencies. Proceedings of Symposium on Watershed Management, Logan, Utah, pp. 306-326.

Solomon, R. M., P. F. Ffolliott, M. B. Baker, Jr., and J. R. Thompson. 1976. Computer simulation of snowmelt. USDA Forest Service, Research Paper RM-174, 8 p.

Solomon, R. M., P. F. Ffolliott, M. B. Baker, Jr., G. J. Gottfried, and J. R. Thompson. 1975b. Snowmelt runoff efficiencies in Arizona watersheds. Agricultural Experiment Station, University of Arizona, Research Report 274, 50 p.

Tennyson, L. C., P. F. Ffolliott, and D. B. Thorud. 1974. Use of time-lapse photography to assess potential interception in Arizona ponderosa pine. Water Resources Bulletin 10:1246-1254.

Timmer, M. J., P. F. Ffolliott, and M. B. Baker, Jr. 1984. Snowpack dynamics in aspen stands near the San Francisco Mountains, Arizona. Hydrology and Water Resources in Arizona and the Southwest 14:51-55.

Thorud, D. B., and P. F. Ffolliott. 1972. Development of management guidelines for increasing snowpack water yields from ponderosa pine forests in Arizona. Proceedings, Symposium on Watersheds in Transition Fort Collins, Colorado, USA, pp. 171-174.

Warren, M. A. 1974. Snowpack dynamics in relation to inventory-prediction variables in Arizona mixed conifer. Master's Thesis, University of Arizona, Tucson, Arizona, 69 p.

Warren, M. A., and P. F. Ffolliott. 1975. Describing snowpack in Arizona mixed conifer forests with a storage-duration index. Hydrology and Water Resources in Arizona and the Southwest 5:87-89.

Wilm, H. G. 1948. The influence of forest cover on snow melt. Transactions of the American Geophysical Union 29:547-556.