CONTRIBUTIONS OF SNOW RESEARCH TO FOREST WATERSHED MANAGEMENT IN THE SOUTHWESTERN UNITED STATES

Peter F. Ffolliott and Gerald J. Gottfried*

ABSTRACT

Snowpacks that accumulate on high-elevation forested watersheds are an important source of water in much of the southwestern United States. However, snowpacks in this region differ from those in more northern regions because of the variability in annual snowfall accumulations and the intermittent melting throughout the winter season. Snow research over the past 50 years has indicated that there are possibilities of increasing snowmelt-runoff through the implementation of forest management practices. The effects of these forest management practices can often be predicted from inventory-prediction relationships. Other research has resulted in development of snow-runoff forecasting procedures and simulation models of forest snowpack dynamics leading to increased knowledge of snow hydrology.

INTRODUCTION

Less than 10% of the annual precipitation in the southwestern United States is recovered for human use. Most of the remaining precipitation is lost to the atmosphere through evapotranspiration. The possibility of increasing the amount of recoverable precipitation from high-elevation forested watersheds is greater for snow than for rain. Snow that accumulates throughout the winter provides a reservoir of water that is potentially available for downstream use in the spring. Between 3.7 and 6.3×10^9 m^3 of water can be held in storage in the high-elevation snowpacks prior to snowmelt in the spring (Ffolliott et al. 1989, Ffolliott 1993). If an additional 5% of the water in these snowpacks was recovered for use, water supplies could be increased by between 185 to 325 million m^3 annually. The additional water could be available to refill downstream reservoirs, recharge groundwater aquifers, or help to satisfy other societal needs.

Much has been learned over the past 50 years about increasing the amount of recoverable high-quality water from snowpacks on forested watersheds in the southwestern United States. Empirical and physically-based studies have been conducted by management agencies and universities to formulate and evaluate basic snow hydrology relationships, develop forest management-snowpack guidelines, and obtain user-friendly methods of predicting the effects of forest management on snowpack water yields. A summary of this snow research is presented in this paper. Readers are encouraged to consult the cited articles for more details.

SNOWPACK CONDITIONS

Winter precipitation patterns produce a few wet years interspersed with several average and many below average years in Arizona and New Mexico (Diaz 1983). These fluctuations are reflected in the snowpack buildups on the high-elevation forested watersheds. The shallow and generally intermittent snowpacks that often characterize the region can disappear between successive storms. As a consequence, the snowpacks vary greatly in their contributions to the flow of water from these upstream watersheds to downstream users.

The low-frequency but often high-magnitude snowfalls that occur throughout the southwestern United States skew the frequency distribution of these events and, as a result, influence long-term measures of central tendency for snowpack conditions. Therefore, median values offer a more meaningful measure of "normal" snowpack conditions than the mean (average) statistic (Jones and Brazel 1986). Snowpack-water equivalents measured in the Salt River Basin of central Arizona every March 1 from 1965 to 1985, expressed as a percentage

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* Professor, School of Renewable Natural Resources, University of Arizona, Tucson, Arizona, and Research Forester, Rocky Mountain Research Station, USDA Forest Service, Phoenix, Arizona.

of the average March 1 values, ranged from less than 15 to more than 250%, confirming that the medium can be a better measure of central tendency of snowpack water equivalents than the mean. The results from relatively short-term research must be interpreted in light of this inherent variability in snowpack conditions and, importantly, extrapolations of the findings from one year to other years must be carefully made.

THEORETICAL AND PROCESS STUDIES

Results from theoretical and process studies allow hydrologists and watershed managers to better understand the causal nature of the relationships between snowpack conditions and forest overstories on a watershed basis. The effects that forest management practices have on snowpack conditions are often estimated from the results of these studies. The results of these studies also provide a fundamental cause-and-effect basis to help explain the results from the more empirical investigations.

Theoretical Studies

The few theoretical studies conducted in the region centered largely on synthesis of mathematical models to describe the nature of short- and long-wave solar radiation exchanges between snowpacks and the overhead forest canopies. The varying extent, duration, and magnitude of these energy transfers depend on the existing forest canopy structures and densities (Bohren 1973, Bohren and Thorud 1973, Bohren and Barkstrom 1974). Forest canopies block some short-wave radiation, emit long-wave radiation, and reflect short- and long-wave radiation from the snowpack. Therefore, the effects of manipulating forest overstories on short- and long-wave solar radiation transfers, and, as a result, the consequent accumulation and subsequent ablation of snowpacks are predictable in a theoretical sense.

Process Studies

Snow intercepted by forest canopies has often been considered as a loss of water to streamflow and soil recharge, largely because the intercepted snow is more exposed to evaporation and sublimation losses than snow that reaches the forest floor. In considering this supposition, researchers evaluated the deposition of intercepted snow in tree canopies with time-lapse imagery to determine the relative significance of snowfall interception in the water budget (Tennyson et al. 1974). It was discovered that much of the snow that is intercepted by the forests of the southwestern United States eventually reaches the ground by snowslide, wind erosion, or canopy melt. The potential loss to snowmelt-runoff by vaporization of canopy snow appears to be relatively small in comparison to how much snow eventually falls to the snowpack on the ground either directly or indirectly from the tree canopies.

Snowmelt rates, timing of the melt, and site characteristics that are related to snowpack behavior under different densities of forest overstories have been evaluated in lysimeter studies. It has been found that energy-budget indices such as average degree-days and average daily solar radiation loads were significantly related to the magnitude of snowmelt outflow from the lysimeters (Jones et al. 1976). Comparisons of the timing of snowmelt outflow beneath lysimeters located on hillslope sites with fluctuations in the streamflow regimes of nearby watersheds show that the outflows from the lysimeters preceded streamflows on these watersheds by variable but predictable time lags (Jones et al. 1976, Gottfried and Ffolliott 1980). Streamflows resulting from the occasional but often widespread rain-on-snow events leading to flooding and a disruption of hydrologic functioning on larger river basins lag further behind the streamflows from upland watersheds and are more unpredictable (Ffolliott and Brooks 1983).

Losses of snow cover as small as 25% and as much as 70% have been attributed to melting alone or (more commonly) a combination of melting, evaporation, and sublimation. The factors influencing evaporation and sublimation of the snow cover on a watershed include site characteristics (aspect, slope, etc.), latitude, distance from the ocean, and average elevation of the watershed (Avery and Dexter 1991, Avery et al. 1992). Sublimation rates are generally higher for the northerly sites, inland sites, and for those sites at high elevations.

SNOWPACK DENSITY

Studies to evaluate the usefulness of snowpack density as an index of snowpack metamorphosis and ripening in the forests of the southwestern United States indicate that an average snowpack density between 350 and 400 kg m^{-3} represent ripe snowpack conditions at which point any additional inputs of energy will cause the snowpack to melt and yield water (Gary 1967, Ffolliott and Thorud 1969, Ffolliott and Thompson 1977, Ffolliott 1985). High snowpack densities occur earlier under sparsely stocked forest stands because of their higher transmissivities, suggesting that forest management activities that reduce the densities of forest stands might also affect the ripening of snowpacks. However, the relationships between snowpack densities and other predictive variables including potential solar radiation and elevation are either statistically non-significant or possess little predictive value (Ffolliott 1985).

FOREST MANAGEMENT PRACTICES

Forest management practices that might increase recoverable water yields from snow include reducing forest densities, clearing forest overstories, and combinations of these two silvicultural treatments. Varying intensities of forest thinnings and differing arrangements, sizes, and patterns of forest clearings are possible. Much of the earlier snow research in the southwestern United States has focused on identifying and quantifying the effects of thinning and clearing forest overstories on snowpack accumulation and melt patterns.

Reducing Forest Densities

Inventory-prediction relationships describing snowpack conditions on high-elevation forests from readily available or easily obtainable input data show that snowpack-water equivalents generally increase as forest densities decrease (Ffolliott and Hansen 1968, Ffolliott and Thorud 1972, Warren and Ffolliott 1975, Timmer et al. 1984). With these inventory-prediction relationships, managers are able to prescribe intensities of thinning treatments to increase snowpack-water equivalents on-site. Unfortunately, many of these inventory-predictive relationships have been confounded by the year-to year variations in snowpack water equivalents. Therefore, historical data from snow courses established by the USDA Soil Conservation Service (re-named the USDA Natural Resources Conservation Service in 1993) have also been analyzed to determine whether basic inventory-prediction relationships evolving from short-term studies remain the same from year-to-year. Of 18 snow courses with 10 or more years of record studied, 15 of the courses supported the hypothesis that with a given snowfall input, the distribution of snowpack water equivalents is determined largely by the spatial arrangements of the surrounding forest overstory (Ffolliott et al. 1972). While snowpack water equivalents changed from year-to-year as a function of the snowfall input, the trade-off between increasing snowpack water equivalents and decreasing forest densities remains unchanged in time.

The usefulness of storage-duration values to provide information for assessments of temporal snowpack conditions has also been investigated. Storage-duration values are obtained for a site by adding together snowpack water equivalent measurements on successive sampling dates (Wilm 1948). Maximum values represent situations of high initial storage and slow melt, while minimum values show low initial storage and rapid melt. Studies have shown that maximum storage-duration values are typically associated with low forest densities, cool sites, and high elevations, while minimum storage-duration values are associated with high forest densities, warm sites, and low elevations (Ffolliott and Thorud 1973, Warren and Ffolliott 1975). A manager can modify the storage-duration of a snowpack on a site through forest management activities.

Clearing Forest Overstories

Research shows that greater accumulations of snow for possible conversion into recoverable runoff water are available in cleared forest openings than under tree canopies (Ffolliott et al. 1965, Hansen and Ffolliott 1968, Gary 1974, Plasencia et al. 1984). The greatest accumulations of snow are found in cleared strips and patches that are less than 1½ H (H = average height of adjacent trees) in size. The increased snow in the openings is partially associated with a reduction in snowpack accumulations in the adjacent forest. However, while clearing forest overstories affects snowfall accumulation and melt patterns, the amount of snow that falls onto the watershed remains unchanged. Only a redistribution of snow on the watershed occurs.

The tradeoffs between increases in the snowpack water equivalents and the volume of overstory removed in creating the forest clearings can be described in a two-dimensional format that indicates where increases or decreases in snowpack water equivalents across snowpack profiles in and adjacent to the forest clearings occur. Three-dimensional time-space models can further describe snowpack conditions in and adjacent to the cleared openings in terms of the volumetric content of water in the snowpack (Ffolliott 1983). Information obtained from these models can be helpful to managers when increased water yields from snowpacks are a watershed management objective.

Timing of Snowmelt

Management activities involving reducing forest densities and clearing forest overstories in different forest types can change the timing of snowmelt-runoff on large watersheds supporting a diversity of mixed forest types. For example, it is desirable to favor a Douglas-fir rather than a aspen forest if the management objective is delay snowpack depletion at lower elevations (Gary and Coltharp 1967). At higher elevations, the similarity in snowpack conditions in spruce-fir forests and mountain grasslands and the delay in snowpack depletion in spruce-fir forest suggest two possibilities. Management to delay snowpack depletion and snowmelt-runoff favors spruce-fir forests with limiting thinning in old-growth stands on the "warmer" sites. Management to maximize snowmelt and peak runoff requires clearing the forest overstory.

RUNOFF EFFICIENCIES

An important step in the development of forest management practices for increasing the amounts of recoverable water from snow involves identification of the physical and climatic factors that influence snowmelt-runoff regimes. One measure of the effects of factors on the quantity of snowmelt-runoff from a watershed is runoff efficiency, which is the portion of a snowpack's water equivalent converted into snowmelt-runoff (Ffolliott and Hansen 1968, Thorud and Ffolliott 1972). Managers interested in reducing forest densities or clearing forest overstories to increase snowmelt-runoff are advised to implement these practices on sites with high runoff efficiency values whenever possible.

Both fixed and variable factors of a site influence the runoff-efficiency value. Fixed factors of importance include slope percent and aspect, soil type and depth, and watershed configuration. Among the variable factors are year-to-year differences in the rates of snowmelt on the site and antecedent soil moisture conditions. Depending largely on the amount and timing of the snowfall, runoff efficiencies from peak seasonal accumulation to the cessation of snowmelt-runoff on a particular watershed can range from 20 to 45%. Runoff efficiencies vary from 25 to almost 90% among watersheds in a particular year, with much of this difference attributed to physiographic features (Solomon et al. 1975a).

Runoff efficiency values are predicted from variables measured before peak seasonal snowpack accumulation and during the snowmelt-runoff regime (Solomon et al. 1975b). Equations for predicting runoff efficiency from measurements obtained before peak seasonal snowpack accumulation can be used to estimate the portion of a snowpack that might eventually be converted into snowmelt-runoff in a season. Other equations that estimate runoff efficiency after the end of a season's snowmelt-runoff period are used to characterize a watershed's hydrologic properties from past runoff-efficiency history and water-yielding potentials. High-elevation forested watersheds experiencing the greatest peak seasonal snowpack accumulations generally have the most efficient snowmelt-runoff regimes. Therefore, forest management practices that are implemented to increase snowpack water equivalents at peak seasonal accumulation have the greatest potential for snowmelt-runoff improvement.

SNOWPACK CHEMISTRY

Research has shown that water contained in the snowpacks of the southwestern United States is high in purity. Concentrations of chemical constituents such as K, Na, Ca, Mg, F. Cl, NO^3, and SO^4 are generally low and there is little evidence of higher than "typical concentrations" of these chemicals in the region (Ffolliott and Lopes 1993). Concentrations of these chemicals in snowmelt-runoff water are also less (for most constituents) than the water quality criteria established by the U.S. Environmental Protection Agency (Environmental Protection Agency 1980) for aquatic life, irrigation, and public water supplies. However, the cause-and-effect linkage between the chemical concentrations in snowpacks and those in the subsequent snowmelt-runoff is unknown.

The pH of these snowpacks was higher than the 5.1 to 5.6 values generally reported for snowpacks elsewhere in the western states (Ffolliott and Lopes 1993), suggesting that the snowpacks are more "alkaline" than those sampled elsewhere. This situation was expected, however, because of the relatively low levels of atmospheric pollutants and lack of local contamination in the high mountains of the region.

REMOTE SENSING OF SNOWPACK CONDITIONS

Intensive inventories of snowpack conditions are uneconomical to implement on larger watersheds. However, estimating snowpack conditions from measurements obtained through remote sensing techniques is a viable alternative. Aerial photography and satellite imagery have been evaluated in terms of their respective usefulness in inventorying snowpacks to predict subsequent snowmelt-runoff volumes.

Aerial Photographs

Relating peak seasonal snowpack accumulation to topographic and forest overstory attributes measured on 1:3,000, 1:6,000, and 1:15,840 black-and-white aerial photographs or photography of comparable resolution has proven successful at a local level (Larson et al. 1974). Only topographic attributes need to be measured and any of the tested photo scales can be utilized to estimate peak seasonal snowpack accumulations on sites where slope steepness and aspect vary widely on a watershed and a diversity of forest overstory densities and tree size classes are intermixed. Average total height of the dominant stand and the percent of total overstory crown cover must also be measured on nearly level sites where forest overstory densities and tree size classes are homogeneous. The 1:15,840 photo scale was significantly better than the other photo scales for obtaining these latter measurements. As already mentioned, knowledge of peak seasonal snowpack accumulation is important to estimate the potential snowmelt-runoff volumes from the region's watersheds.

Satellite Imagery

Measures of snowpack depletion are highly correlated with the volume of snowmelt-runoff in the southwestern United States, where snowpacks are shallow and often intermittent in contrast to the snowpack conditions in other regions in the western states (Ffolliott et al. 1989, Ffolliott 1993). In evaluating the use of satellite imagery in snowmelt-runoff forecasts, researchers related measurements of snow cover obtained from LANDSAT imagery to subsequent snowmelt-runoff volumes during the snowpack depletion period in a year (1972-73) of heavy snowfall (Aul and Ffolliott 1975, Ffolliott and Rasmussen 1976). Imagery in the red band was used in this study because snow cover can most easily be detected in the spectral range. A highly significant ($r^2 = 0.995$) linear relationship between the extent of snow cover (km^2) and snowmelt-runoff (m^2) between the dates of snow-cover measurement in the depletion period was obtained. Although this relationship was developed for a year of heavy snowfall, relationships of this general form have been incorporated into snowmelt-runoff forecasting procedures because of the high correlation (Rasmussen and Ffolliott 1981).

SIMULATION MODELS

Simulation models are useful in estimating the effects of proposed forest management practices on snowpack dynamics and then selecting a course of action to meet a specified purpose from these estimates. Simulators have been developed by researchers to estimate snowpack accumulation, redistribution, and melt; the amount of snowmelt potentially contributing to snowmelt-runoff; and the resulting snowmelt-runoff regimes on a watershed-basis.

Snowpack Conditions

Snowpack conditions on site at a point-in-time reflect the combined effects of accumulation, redistribution, and melt processes that occurred before that point-in-time. User-friendly, highly interactive simulation models have been developed to help in separating the inherent complexities of these processes and, by doing so, allow managers to implement forest management activities that are likely to manipulate snowpack conditions in a manner that is hydrologically favorable to increasing snowmelt-runoff events (Ffolliott and Rasmussen 1979). The embedded modular components simulate snowpack water equivalent before a forest management practice is implemented to provide a benchmark to compare outputs following a simulated reduction of forest densities or clearing of forest overstories. These simulation models are useful in empirically quantifying on-site snowpack accumulation, redistribution, and melt processes within a dynamic framework. The input data needed to execute the simulation models are readily available or easily obtained by the manager.

On-Site Snowmelt

Knowing the contributions of the melting snowpacks to runoff regimes is also necessary. Modification of aa on-site snowmelt simulation model for the Colorado subalpine forests (Leaf and Brink 1973) provides predictions of the contributions of the relatively shallow and intermittent snowpacks in Arizona and New Mexico to runoff. This more generalized model requires only limited knowledge of watershed condition and snowpack parameters (Solomon et al. 1976). The driving variables in the simulator are daily values of maximum and minimum air temperatures, precipitation amounts, and impinging solar radiation loads. Verification of the model on watersheds representing a range of conditions common to high-elevation forested watersheds has been satisfactory. Interrogation of the model provides information on watershed conditions that are most favorable to potential increases in snowmelt-runoff volumes.

Because solar radiation measurements are not always available for a simulation exercise, relationships have been developed to predict direct and diffuse solar radiation values from commonly observed cloud-cover characteristics (McAda and Ffolliott 1987). These relationships have been incorporated into the more generalized snowmelt simulator (Solomon et al. 1976) as subroutines to index the required solar radiation variable when actual measurements of solar radiation are not available.

Snowmelt-Runoff

Computer simulation models have also been developed to estimate the impacts of forest management practices on snowmelt-runoff regimes on a watershed. One of these computer models contains modular components to estimate either rainfall-runoff or snowmelt-runoff events. This model has a user-friendly, interactive format to facilitate its operation by managers at remote locations (Larson et al. 1979, Rasmussen and Ffolliott 1981, Ffolliott and Guertin 1988). The driving variable in the model is daily precipitation amount. Initialization values for stored soil moisture and average forest density are also required. Outputs are values representing daily runoff, changes in soil moisture, evapotranspiration, and deep seepage. Large heterogeneous watersheds are separated into similar hydrologic response units with the simulator applied sequentially to each of the units.

MANAGEMENT IMPLICATIONS

Research results have shown that snowpack accumulation and melt patterns in the southwestern United States can be increased by reducing forest densities or clearing openings in a forest overstory. Predictive relationships are available to estimate the effects of these forest management practices on the accumulation, redistribution, and melt of the snowpacks. Forest management practices can also be designed to accelerate or delay snowmelt-runoff on a watershed-basis to synchronize snowmelt-runoff regimes. These relationships are especially useful to managers because they are based largely on input variables that are easily obtained from field measurements or meteorological records. Other research findings have been useful in predicting peak seasonal snowpack accumulations, a key measurement of snowpack conditions, and the following snowmelt-runoff regime. These predictions are based on field and remote sensing techniques, the latter employing aerial photographs and satellite imagery. Some of these techniques have been incorporated into snowmelt-runoff forecasting procedures. Another phase of the research effort has been the development of simulation models for obtaining estimates of snowpack accumulation, redistribution, and melt processes and the resulting snowmelt-runoff events. Many of these models have a user-friendly format to facilitate their operation by managers.

On average, snowmelt-runoff can contribute up to two-thirds of the annual water yields from high-elevation forested watersheds in the region (Ffolliott and Baker 2000, Baker and Ffolliott 2003). However, larger increases can occur in wet years, when the soil mantle has been recharged before snowmelt began, while little or no increase in snowmelt-runoff volume might occur in dry years, when most of the snowmelt-runoff recharges the soil mantle. In either case, the duration of the changes in annual snowmelt-runoff volumes that are attributed to the implementation of forest management practices depends largely on the condition of the watersheds both before and after the forest management practices are implemented (Baker 1999). Depending on the site conditions, these changes are likely to diminish in 20 years or less to the levels of streamflow observed before the forest management practices were implemented without further management.

CONCLUSIONS

Theoretical and process studies, empirical field research, and simulation investigations provide a basis for the development of forest management practices to enhance snowmelt-runoff on high-elevation forested watersheds of the southwestern United States. Forest management practices can be designed to increase the amount of recoverable water from melting snowpacks on watersheds with high-runoff efficiencies while achieving silvicultural objectives. However, the issue of whether forest management practices can be (or will ever be) implemented solely to alter snowpack dynamics is unresolved. The emphasis of watershed management has changed from only a focus on increasing water supplies to a more holistic perspective of natural resource management. Current watershed management also considers other ecosystem-based, multiple-use values of watershed lands including forage, wildlife, and recreational use. These concerns have been identified through society's expressions about the future management of watersheds and natural resources.

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