THE SOUTHWEST'S FROZEN ASSETS: SNOWPACK MANAGEMENT

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By

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Introduction

In the arid Southwest (specifically, Arizona and New Mexico), less than 10 percent of the annual precipitation input is recovered for use by man. A large portion of the precipitation input that is recovered for use originates on high elevation, forested watersheds. Even here, 80 to 90 percent of the precipitation input is currently unavailable for downstream users. However, it is potentially available, at least in part, if water yields can be increased.

The possibility of increasing the amount of recoverable water from forested watersheds appears greater for snow than for liquid rainfall. Snow generally accumulates on forested sites throughout the winter, providing a large reservoir of stored water potentially available for use in the spring. For the Southwest as a whole, between 2 1/2 and 5 million acre-feet (or approximately 310,000 to 620,000 hectare-meters) of water can be in storage in the form of snowpacks just prior to the beginning of snowmelt runoff in the spring. If snowmelt water yields were increased by 10 percent, for example, an additional 250,000 to 500,000 acre-feet (or approximately 31,000 to 62,000 hectare-meters) of water may be realized annually to help meet increasing municipal, industrial, and agricultural demands, along with future energy requirements.

The importance of snow in the water budget of the Southwest is further evidenced by the significant role snowmelt plays as a source of runoff and water yield for the reservoir systems in the area. On the Salt-Verde River Basin in north-central Arizona, for example, snowmelt runoff accounts for approximately two-thirds of the mean annual streamflow (Warskoe 1971).

With much of the snowmelt runoff occurring on forested watersheds, it has been suggested that forest management activities could be employed to enhance snowmelt water yield, assuming that trees and their spatial arrangement affects the snow regime. Research in the Southwest and elsewhere has indicated that forest management activities do affect the snowpack and appear to cause increased snowmelt runoff. Furthermore, there is reason to believe that the thinning and clearing of forest overstories to increase snowmelt water yield can be made compatible with existing demands for wood, forage, and wildlife, and recreational use of forest lands.

A review of various snow research efforts conducted in the Southwest over the past decade is presented herein to illustrate some of the possibilities for enhancing snowmelt water yield. These efforts, which have largely been cooperative studies involving the Forest Service, the Soil Conservation Service, the universities, and various user groups, have been aimed at the development of snow management guidelines to increase the amount of recoverable water derived from snowpacks on forested watersheds.

Conceptual Background

Considering the use of forest management activities in attempting to increase recoverable water yield from snow, two basic options are available:

1. Reducing Forest Densities - thinning practices, including various intensities and combinations of intensities.

2. Removing Forest Overstories - clearing practices, including different arrangements and patterns.

Water yield improvement experiments have demonstrated that increased snowmelt runoff may result from a reduction or removal of forest overstories. However, the specific hydrologic mechanisms involved have not been completely identified or quantified. It is

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known that more snow accumulates under sparsely stocked forest stands and in clearings in forest overstories. These greater accumulations of snow may, in turn, contribute to increased runoff. If this hypothesis is accepted, and if the water equivalent of a snowpack can be maximized just prior to spring runoff by forest management activities, perhaps the quantity of useable runoff can also be maximized.

The assumption that maximum runoff occurs from maximum snow accumulation provides a basis for testing a variety of forest thinning and clearing options because changes in snow accumulation in situ, resulting from forest management activities, can be measured. Therefore, management activities that cause increases in snow accumulation just prior to spring runoff can be identified for given forest conditions.

Another step in the development of forest management guidelines for increasing snowpack water yield involves the identification of physiographic and climatic factors which determine, in part, the quantity of runoff yielded. Conceivably, comparable forest management activities on two sites with similar vegetative characteristics may yield different amounts of runoff if the sites have differing slope-aspect combinations, soil characteristics, or precipitation-temperature regimes. It may be desirable, therefore, to implement water yield improvement programs on sites with the greatest apparent water yield. In this case, the decision would be based on physiographic and possibly climatic factors, since vegetation conditions are the same.

One measure of the effect of physiographic and climatic factors on the amount of runoff yielded is runoff efficiency, defined as that portion of a snowpack that is converted into recoverable surface water (Thorud and Ffolliott 1972). Conceptually, both fixed and variable factors determine runoff efficiency. Fixed factors include soil depth and type, slope percent, aspect, and basin configuration; while variable factors include year-to-year differences in antecedent moisture conditions and rates of snowmelt.

Reducing Forest Densities

To evaluate the affect of reducing forest densities on snowpack conditions, inventory-prediction relationships describing snowpack conditions associated with different forest densities common to the Southwest have been developed (Ffolliott and Hansen 1968, Ffolliott and Thorud 1972). These relationships are often based on readily available or easily obtained expressions of forest attributes. Specific relationships have been synthesized to describe the peak seasonal accumulation just prior to spring runoff. As expected, snowpack accumulations decreased as forest densities increased, which is consistent with studies reported by others. Therefore, it has been presumed that, although a land manager may have little opportunity to affect runoff efficiency, he may be able to define forest management activities that will increase the snowpack water equivalent that is available for conversion into recoverable water.

In an attempt to alleviate the problem of basing conclusions on relatively short-term studies, which are often confounded by year-to-year differences in snowfall, historical data from several Soil Conservation Service snow courses have been analyzed to determine whether relationships between snowpack water equivalent and forest densities remain the same from year-to-year (Ffolliott, Thorud, and Enz 1972). The hypothesis tested in this study and evaluated statistically by analyzing the family of regression lines representing each of 18 different snow courses was that, given a precipitation input, the distribution of snowpack water equivalents is primarily determined by the spatial arrangement of the forest overstory. Of the 18 snow courses analyzed, 12 supported this hypothesis, indicating that, while snowpack water equivalents may change as a function of precipitation inputs, the trade-off between snowpack water equivalent and forest densities may remain relatively unchanged.

Most of the studies attempting to quantify snowpacks in relation to inventory-prediction variables have been based on empirical relationships for a single point-in-time, while little work has been directed toward an evaluation of snowpack conditions over time during a given season. To provide information for dynamic assessments, studies have been conducted in the Southwest to evaluate the usefulness of a storage-duration index (Wilm 1948) in the development of forest management activities for water yield improvement (Ffolliott and Thorud 1973, Warren and Ffolliott 1975). This index, which is synthesized by adding together snowpack water equivalent measurements made on successive sampling dates, is considered to be an integrated single measure of initial snow storage and subsequent snowmelt. Theoretically, maximum index values are obtained with high initial storage and slow melt, while minimum index values are characterized by low initial storage and rapid melt. Studies in ponderosa pine and mixed conifer forests have shown high initial snow storage and slow melt associated with low forest densities, cool sites, and high elevations; sites exhibiting these conditions possessed maximum storage-duration index values. Low initial snow storage and rapid melt was associated with high forest densities, warm sites, and low elevations.

Removing Forest Overstories

Another option available to a land manager attempting to increase snowpack water yield is to create openings of different shapes and orientations in forest overstories. Work carried out in the Southwest (Ffolliott, Hansen, and Zander 1965, Hansen and Ffolliott 1968, Gopen 1974) and elsewhere indicates that openings created in forest overstories often increase snowpack accumulations within the openings; therefore, greater accumulations of snow may be available prior to the start of runoff than would otherwise be the case at these locations. However, while clearing forest overstories has been shown to affect snowfall distribution patterns, it is not always known whether an increase in snow-pack water equivalent on the watershed as a whole has occurred.

Techniques to evaluate snowpack profiles in and adjacent to forest openings have been developed. Initially, this work led to the synthesis of a two-dimensional analytic procedure for estimating whether an increase (or decrease) in snowpack water equivalent occurred at a point-in-time in and adjacent to a forest opening (Ffolliott and Thorud 1974). In addition, the trade-off between the increase (or decrease) in snowpack water equivalent and the forest overstory removed in creating the opening was identified.

In one case study, presented here to illustrate the above procedure, the snowpack water equivalent in and adjacent to a clearcut strip 67 feet (or approximately 20.5 meters) wide and oriented with the long-axis up-and-down a 15 percent slope increased 60 percent (30.5 millimeters) when compared to the snowpack water equivalent outside the apparent effect of the clearcut (Ffolliott and Thorud 1974). In this example, 46 percent (24.5 cubic meters) of the forest overstory in the zone of influence was removed in creating the opening. The zone of influence, by definition, is the area to the windward and leeward of an opening which has measurable differences in snowpack water equivalent as compared to conditions further from the opening (Hansen and Ffolliott 1968). Therefore, in this case study, an estimated increase of 60 percent in snowpack water equivalent occurred when 46 percent of the forest overstory was removed. While this illustration represents only one site at a single point-in-time, comparable measurements over an array of sites may provide quantitative information regarding the effects of creating openings in forest overstories to increase snowpack accumulation over entire watersheds.

Subsequent work has led to the synthesis of a three-dimensional model to describe snowpack conditions in and adjacent to forest openings over time during a snow season (Gopen 1974). This space-time model provides information which may be utilized to maximize (or minimize) the "net" effect of forest openings on snowpack accumulation (and perhaps water yield), depending upon the objectives of management. Also, knowledge generated by this model may aid the land manager in decisions concerning the specific location and size of proposed timber cuts in situations where increased water yield from snowpacks is a consideration.

The removal of Douglas-fir forest overstories by timber harvesting activities frequently results in a subsequent establishment of aspen forests which, in turn, may affect snowpack accumulation and melt. Exploratory work in the Southwest has indicated that, at peak seasonal accumulation, the snowpack water equivalent on cool sites is higher in aspen forests than in Douglas-fir forests; snowpack accumulations were essentially the same on warm sites (Gary and Coltharp 1967). With respect to snowpack depletion, the rates were generally higher under aspen forests than Douglas-fir forests. Therefore, it appears that the conversion of Douglas-fir forests to aspen forests through vegetation management may affect the timing of snowmelt runoff, specifically by increasing the rate of snowpack depletion.

Process and Theoretical Studies

Several process and theoretical studies have been carried out in an attempt to better understand relationships between snowpack conditions and forest overstories in the Southwest.

Interception of snowfall by forest canopies may change the timing, amount, and areal distribution of water input on a watershed, and thereby affect subsequent useable water supplies that originate as snowmelt runoff. Consequently, a knowledge of the interactions between snowpack dynamics and forest overstories could be helpful in the implementation of water yield improvement programs involving forest management activities.

The behavior of intercepted snow on a stand of uneven-aged ponderosa pine has been evaluated with the use of a super 8-mm time-lapse camera (Patton, Scott, and Boeker 1972) to determine the relative significance of snowfall interception in the water budget of this forest (Tennyson, Ffolliott, and Thorud 1974). Specifically, a snow load index, expressed as the ratio of forest canopy area covered with snow to the total canopy area, was developed to estimate interception storage for trees in the field of camera view for discrete time periods. The snow load index, time-lapse photographs, and associated climatic data were then combined to describe accumulation on the canopy, and to identify and rank, according to relative magnitudes, the basic processes of canopy snow removal. The rate of snow accumulation was nonlinear, with initial storage being rapid and then slowing with time. Most of the intercepted snow appeared to reach the snowpack on the ground by snowslide and wind erosion, or by canopy snowmelt and, therefore, was not considered a significant loss to the water budget on the site. The potential loss to streamflow by vaporization of canopy snow and canopy meltwater appeared minimal relative to the magnitudes of snow which eventually reached the snowpack by one means or another.

In another study, lysimeters were installed to characterize snowmelt rates, timing of melt, and site differences in snowpack behavior under a ponderosa pine forest (Jones, Ffolliott, and Thorud 1976). While the ablation of a given snowpack water equivalent is necessarily partitioned into either liquid melt or water vapor, determinations, as obtained in this study, were helpful in further understanding the water budget on a site. Interestingly, but based on a relatively limited sample, no significant differences were found in several snowpack parameters (accumulated snowpack water equivalent and subsequent snowmelt rate) among open and forested sites. An empirical relationship between snowmelt beneath the lysimeters and various energy budget parameters provided estimates of daily snowmelt outflow from the lysimeters, suggesting the possibility of prediction opportunities on an operational scale. In comparing snowmelt outflow beneath the lysimeters with streamflow from a nearby watershed in regards to the timing of outflow, expressed as a percentage of seasonal total, streamflow from the lysimeters preceded streamflow from the watershed; furthermore, the runoff efficiency on-site was greater than that for the watershed as a whole, which is to be expected conceptually.

Theoretical studies of snowpack-forest overstory interactions have been undertaken in the Southwest to supplement and, hopefully, refine the information developed from the empirical and process-oriented investigations described above. To date, the theoretical studies have primarily concentrated on the synthesis of models of short-wave and long-wave radiation exchange between snowpacks and forest canopies (Bohren 1973, Bohren and Thorud 1973, Bohren and Barkstrom 1974). Radiation, a major source of energy in the snowmelt process, varies partly as a function of the forest canopy structure. Therefore, if models that describe the effect of forest canopies on short-wave and long-wave radiation transfers can be developed, the build-up and ablation of snowpacks may become more predictable, particularly as influenced by forest management activities.

It is anticipated that future theoretical work will be directed toward acquiring an understanding of the nature of vapor pressure gradients associated with snowpacks in a forested environment. As the dynamics of vapor pressure gradients determine, in part, the rate at which snowpacks ablate and the partitioning of snowpack water equivalent into liquid water and water vapor, such an effort is considered important in the development of forest management activities for increasing snowpack water yield.

Determination of Runoff Efficiencies

Conceptually, snowpack water yield is dependent upon two general factors: the snowpack accumulation on-site, and the snowmelt runoff efficiency. While research efforts continue to be directed toward analysis of the first factor, new knowledge is also being gained regarding the second.

To develop an understanding of the magnitudes and ranges of snowmelt runoff efficiencies in the Southwest, efficiencies have been documented for several experimental watersheds where snowmelt water yield is a significant contributor to the annual water yield (Solomon, Ffolliott, Baker, Gottfried, and Thompson 1975). Basic descriptive data for 14 experimental watersheds, with a combined total of 32 data-years, indicate that snowmelt runoff efficiencies can vary greatly from year-to-year on a given watershed, and from watershed-to-watershed in a given year. To illustrate, runoff efficiencies for the time period from peak season snow accumulation to cessation of snowmelt runoff have varied from 20 to 45 percent on a given watershed, depending, at least in part, on the amount of snowfall and the timing of snowfall events in different years. On the other hand, efficiencies have ranged from 25 to 85 percent among watersheds in a given year, with much of this difference being attributed to physiographic features.

Runoff efficiency has also been found to vary within a season on a given watershed. To characterize patterns of changing seasonal runoff efficiencies, data from a series of experimental watersheds have been normalized by plotting accumulated snowpack ablation in percent against accumulated runoff in percent (Solomon, Ffolliott, and Thorud 1975). From these normalized curves, it was determined that no common or distinct pattern described changing efficiencies throughout a season from year-to-year on the selected watersheds. Rather, every year was unique, with some years demonstrating gradual transitions of efficiencies from the beginning to the end of the runoff season, while other years had sharp breaks between the beginning, middle, and end. However, a general trend was observed, with low runoff efficiencies characterizing the initiation of a melt season, graduating into higher efficiencies toward the middle, and finally regressing back to low efficiencies toward the end of the season.

A knowledge of seasonal runoff efficiencied could be useful in predicting snowpack runoff originating on forested watersheds. A first step in the development of predicting techniques is the identification of variables affecting snowpack ablation and surface runoff relationships. To this end, 10 variables which characterize climatic and watershed conditions were correlated with runoff efficiencies obtained from several experimental watersheds (Solomon, Ffolliott, and Thorud 1975). The resultant analysis indicated that moisture conditions antecedent to the snow season, peak snowpack accumulation, and duration of runoff were the only variables significantly correlated with runoff efficiencies; therefore, it is implied that high efficiencies would occur on watersheds that received substantial precipitation prior to the start of snowpack accumulation, possessed a deep snowpack at peak accumulation, and received a large amount of precipitation during the snow season.

In other analyses of runoff efficiencies, empirical predicting equations were synthesized to estimate the portion of a snowpack on a watershed that may be converted into runoff during a snowmelt season (Solomon, Ffolliott, and Thorud 1975). These equations suggest that watersheds with the greatest peak snowpack accumulation and of highest elevation are the most efficient in terms of snowmelt runoff. Therefore, forest management activities imposed to increase snowpack water equivalent at peak seasonal accumulation on watersheds at high elevations would seemingly have superior potential for snowmelt water yield improvement.

Simulation Investigations

Initial attempts have been undertaken to develop computer models designed to simulate the melting of snowpacks in the Southwest. Specifically, a modification of a snowmelt model for Colorado subalpine forests (Leaf and Brink 1973) provides for modeling the intermittent snowpack conditions found in Arizona and New Mexico (Solomon, Ffolliott, Baker, and Thompson 1976). The modified program SNOWMELT is dependent on four daily input variables: maximum and minimum temperatures, precipitation, and short-wave radiation (or percent cloud cover). Only limited knowledge of watershed and snowpack parameters is required to initialize the model. Verification of SNOWMELT on several experimental watersheds representing a range of conditions that are common to high elevation, forested watersheds in the Southwest proved satisfactory.

Conceptually, applications of program SNOWMELT may provide insight as to the rate at which snowmelt is occurring over an array of forested watersheds. Such knowledge, in turn, may suggest ways by which forest management activities may be employed to alter snowmelt rates to maximize runoff and water yield from large areas.

Conclusion

The empirical field work, the related process and theoretical studies, and the associated simulation investigations which have been undertaken in the Southwest will, hopefully, provide guidelines for managing high elevation, forested watersheds from the standpoint of enhancing snowmelt water yield. Furthermore, it seems possible that forest management activities can be designed to improve snowpack water yield, and at the same time provide the timber, forage, wildlife, and amenity values required by society in some optimal combination.

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