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DEVELOPMENT OF MANAGEMENT GUIDELINES FOR INCREASING SNOWPACK WATER YIELDS FROM PONDEROSA PINE FORESTS IN ARIZONA

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Snowmelt on the Salt-Verde River Basin in Arizona yields a major portion (possibly 50 percent or more) of the annual surface runoff that supplies six reservoirs. These reservoirs provide municipal, industrial, and agricultural water for the Phoenix metropolitan and nearby areas. About 30 percent of the Basin ($2\frac{1}{2}$ million acres) is within the ponderosa pine forest zone, where much of the snowmelt runoff originates. Therefore, initial work in the development of forest management guidelines for increasing snowpack water yields is concentrated in this zone. These guidelines, to be effective, must be developed in a context that considers the constraints imposed by management objectives involving the other products and uses (e.g., timber, forage, wildlife, recreation opportunities, etc.) of the land.

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DEVELOPMENT OF MANAGEMENT GUIDELINES FOR INCREASING SNOWPACK WATER YIELDS FROM PONDEROSA PINE FORESTS IN ARIZONA

David B. Thorud and Peter F. Ffolliott[1]

ABSTRACT. Snowmelt on the Salt-Verde River Basin in Arizona yields a major portion (possibly 50 percent or more) of the annual surface runoff that supplies six reservoirs. These reservoirs provide municipal, industrial, and agricultural water for the Phoenix metropolitan and nearby areas. About 30 percent of the Basin (2½ million acres) is within the ponderosa pine forest zone, where much of the snowmelt runoff originates. Therefore, initial work in the development of forest management guidelines for increasing snowpack water yields is concentrated in this zone. These guidelines, to be effective, must be developed in a context that considers the constraints imposed by management objectives involving the other products and uses (e.g., timber, forage, wildlife, recreation opportunities, etc.) of the land.

(KEY WORDS: Snowmelt Runoff, Forest Management, Ponderosa Pine, Arizona.)

INTRODUCTION

Snowmelt is a major source of runoff and water yield for the reservoir systems in Arizona, and it also contributes to the recharge of groundwater aquifers. Much of the snowmelt runoff occurs in the ponderosa pine forest, which suggests using forest management methods to enhance snowmelt water yield if trees and their spatial arrangements affect the snow regime. Basic research indicates that forest management does affect the snowpack [Anderson, 1963; Berndt, 1961; Goodell, 1965; Packer, 1962], and can cause increases in snowmelt runoff [Hoover and Leaf, 1967].

Another aspect of the above-mentioned water yield results supports the feasibility of their ultimate application in operational management programs. There is reason to believe that thinning and clearing of forest overstories can be made compatible with wood, forage, and wildlife production, and recreational use of forest lands.

The goal of the research project discussed in this paper is the development of operational forest management guidelines for increasing water yields from snowpacks in the ponderosa pine type on the Salt-Verde River Basin. This Basin yields runoff for the municipal, agricultural, and industrial developments in the Phoenix and central Arizona area. Since this area is important to the economy and welfare of the State, the project study areas have been centered on the Salt-Verde River Basin. However, the potential results should apply to comparable forest, physiographic, and climatic conditions found elsewhere in Arizona, and may be applicable to forest regions outside Arizona where snow is an important component of the annual water yield.

Background

Considering the use of forest management methods for 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 on experimental watersheds [Brown, 1969; Hewlett and Hibbert, 1961; Reinhart, 1965] have demonstrated that increased snowmelt runoff may result from a reduction or removal of forest overstores; the hydrologic mechanisms involved have not been completely identified and quantified, however. It is known that more snow accumulates in sparsely stocked forest stands, and in clearings in the forest overstory [Anderson, 1963; Goodell, 1965; Hansen and Ffolliott, 1968; Packer, 1962; Rothacher, 1965]. These greater accumulations of snow may contribute to increased runoff from experimental cuts. If this hypothesis is accepted, and if the water equivalent of a snowpack can be maximized just prior to spring runoff by forest management methods, perhaps the quantity of usable 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 methods can be measured. Thus, management practices that cause increases in snow accumulation prior to spring runoff can be identified for given forest conditions.

Another consideration in developing forest management guidelines for increasing snowpack water yields is concerned with the identification of physiographic and climatic factors which determine, in part, the quantity of runoff yielded. Conceivably, comparable forest management methods 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.

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One measure of the effect of physiographic and climatic factors on the amount of runoff yielded is *runoff efficiency*, defined as the percentage of snowpack water equivalent at peak accumulation that appears as runoff [Garn, 1969]. Runoff efficiency on small watersheds in the ponderosa pine forest of Arizona can vary from less than 20 to over 90 percent [Ffolliott, 1970]. Conceptually, both fixed and variable factors determine runoff efficiency. Fixed factors include soil depth and type, slope percent, aspect, and basin configurations. Variable factors include year-to-year differences in antecedent soil moisture conditions and rates of snowmelt.

Development of Investigation Framework

To establish a framework for study which may ultimately lead to forest management guidelines for increasing snowpack water yields, alternative courses of action were simulated. The simulation technique used to achieve an effective and efficient program was based on PERT (Program Evaluation and Review Technique) analyses [Davis, 1968; Everts, 1964]. Essentially, a PERT system identifies the relationships between activities comprising a project, the estimated time required to complete each activity, and the probabilities of success in completing the activities and project within the time constrainst specified. Only relationships between activities in the project have been considered at this stage of the research effort.

The investigation frame work of the research project, as delineated by a PERT analysis, indicates the required activities within the project and the sequential ordering of prerequisite activities. Diagrammatically, study activities are arrows (directed arcs) ending at specified events (Figure 1). Several activities may end at one event, in which case the event occurs only when all activities are completed. Once an event has occurred, succeeding activities may begin.

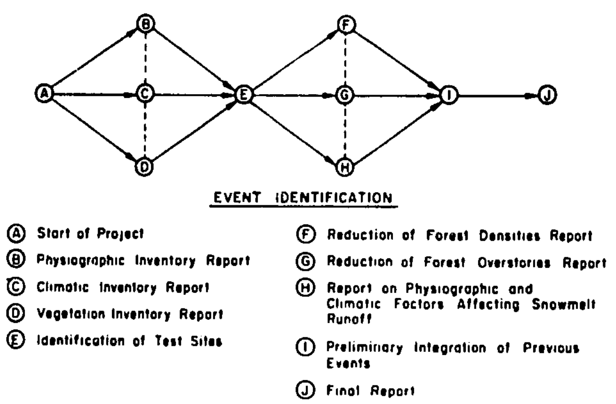

Fig. 1. A PERT network illustration of the investigation framework for a research effort designed to develop forest management guidelines for increasing snowpack water yield.

In the investigation fromework developed for the research discussed in this paper (Figure 1), study activities consist of the following:

1. Identifying pertinent descriptive populations.
   a. Physiographic (arc AB).
   b. Climatic (arc AC).
   c. Vegetative (arc AD).
2. Delineating test sites.
   a. In terms of physiographic features (arc BE).
   b. In terms of climatic features (arc CE).
   c. In terms of vegetative features (arc DE).
3. Implementing experiments.
   a. Reducing forest densities (arc EF).
   b. Removing forest overstories (acr EG).
   c. Effect of physiographic and climatic factors on runoff (arc EH).
4. Developing preliminary evaluations.
   a. Reducing forest densities (arc FI).
   b. Removing forest overstories (arc GI).
   c. Effect of physiographic and climatic factors on runoff (arc HI).
5. Preparing comprehensive report (arc IJ).

Implementation of Investigation Effort

As indicated by the PERT network, identification of pertinent descriptive populations (e.g., physiographic, climatic, and vegetative) is a necessary initial activity. This step is needed to establish sideboards on the array of potential test sites for evaluation. With the completion of this event, priorities regarding the experimental development of forest management methods designed to increase snowpack water yields may be formulated. Given a fixed research effort (e.g., level of funding, manpower, etc.), these priorities will delineate areas of initial and primary concern.

Three inventory evaluations have been, or are currently being conducted to attempt identifications of pertinent populations for investigation. A physiographic evaluation of the ponderosa pine forest on the Salt-Verde River Basin, describing slope, aspect, elevation, and soil interactions associated with this area, has been completed [Ffolliott, Fisher, Thorud, 1972]. The results of this inventory provide a basis for estimating proportions of the Basin exhibiting specific physiographic features.

Currently, climatic and vegetative inventory evaluations are being implemented. The climatic inventory evaluation will spatially identify zones of similar precipitation input, radiant energy components, snowpack accumulation, and snowmelt. In the vegetative inventory, proportions of the Basin that support given forest overstory densities that may affect the snowpack, and subsequent runoff, will be quantified to estimate the operational feasibility of proposed management systems.

Once the inventory evaluations are completed, and pertinent descriptive populations are identified, test sites will be established to represent the hydrologically significant physiographic, climatic, and vegetative features. Hopefully, test sites representing given interacting features can be replicated throughout the Basin. As a minimum goal, however, test sites will be located on areas judged to be potentially high in snowpack water yields, as determined by observed contributions to the reservoir systems.

After test sites have been delineated, studies designed to evaluate (1) forest management methods for increasing water yields from snow (e.g., reducing forest densities and removing forest overstories), and (2) physiographic and climatic factors which may help determine the quantity of snowmelt runoff yielded, will be implemented. Experimental evaluations will analyze a range of forest management opportunities on sites characterized by arrays of runoff efficiencies as described by physiographic and, possibly, climatic criteria. One ultimate goal will be the prescription of forest management methods that will maximize the water equivalent of the snowpack at peak accumulation on sites of high runoff efficiency.

Some exploratory studies of the snow regime as affected by different density levels and clearing patterns in forest overstories have begun, based on preliminary assessments of physiographic, climatic, and vegetative factors. Snow accumulation and melt have been measured on study plots of different forest densities in eastern and north-central Arizona. Based on these measurements, inventory-prediction equations describing snowpack conditions associated with different forest density levels as functions of readily available or easily obtained expressions of forest attributes have been developed [Ffolliott and Thorud, 1972].

The snow regime in artificial forest openings and in natural clearings has been measured on several sites throughout the ponderosa pine type. This initial work has lead to the development of a two-dimensional analytic technique to describe snowpack profiles in and adjacent to forest openings and clearings in terms of whether an increase in water equivalent has occurred at a point in time. Currently, this technique is being expanded to include the third dimension and changes over time. The resulting three-dimensional model will allow predictions to be made of the effect of forest clearing methods on snow accumulation and melt in time and space.

Preliminary assessments of physiographic factors that affect the magnitude of snowmelt runoff has also begun. This assessment utilizes the physiographic inventory (arc AB) to index fixed factors affecting runoff and the climatic inventory (arc AC) to index the variable factors. In addition, the combined effect of fixed and variable factors on runoff efficiency has been empirically evaluated on small watersheds, these data provide some insight on the variability of runoff efficiency in space and time.

Theoretical Studies

Theoretical studies of forest overstory-snowpack interactions are being undertaken to supplement and refine information and models developed from the empirical studies described above [Bohren and Thorud, 1972; Bohren, 1972]. The theoretical studies have concentrated primarily on models of short-wave and long-wave radiation exchange between forest canopies and snowpacks. Radiation is a major source of energy in the snowmelt process [Crops of Engineers, 1956], and it varies as a function of forest canopy structure. Thus, if models that describe the effect of forest canopy structure on short-wave and long-wave radiation transfer processes can be developed, the build-up and ablation of snowpacks may become more predictable, particularly as influenced by forest management practices.

In an initial radiation model, forest canopies of varying closure were represented by an infinite plane, and solar radiation was assumed to be isotropic and uniform [Bohren and Thorud, 1972]. A more advanced model characterizes canopies of varying closure as an infinite slab with a depth dimension, and the solar radiation is angled rather than isotropic [Bohren, 1972]. The latest model will be adapted to predict the spatial and temporal distribution of short-wave and long-wave radiation fluxes to and from snowpacks located in and adjacent to forest openings of various dimensions and orientations. If this modeling effort is successful, land managers will have an additional tool for estimating the effect of cutting practices on the snow regime.

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