CHARACTERIZATION OF ARIZONA SNOWPACK DYNAMICS
FOR PREDICTION AND MANAGEMENT PURPOSES

by

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I hereby recommend that this dissertation prepared under my direction by Peter F. Pollowitc
entitled Characterization of Arizona Thundctr Cellar for Prediction and Management Purposes
be accepted as fulfilling the dissertation requirement of the degree of Doctor of Philosophy

David B. Thorud  April 14, 1970
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ABSTRACT

Inventory-prediction equations describing snowpack water content as functions of readily available or easily obtained inventory variables were developed for use in the ponderosa pine type in Arizona. Although empirical in nature, these equations include parameters assumed to index interception of precipitation inputs, obstruction of direct beam solar radiation, and re-radiation from trees onto the snowpack.

Primary consideration was given to forest cover variables in synthesizing the inventory-prediction equations, because currently proposed water improvement programs designed to increase water yield derived from snow consist essentially of vegetative manipulations. Additional independent variables evaluated include potential direct beam solar radiation, elevation, soil, and precipitation inputs.

All of the inventory-prediction equations describing a particular snowpack condition were not statistically equivalent in terms of the standard error of estimate or the coefficient of determination. Equations including basal area, bole area, volume, and height-index as expressions of forest cover density were generally better than equations with point density, sum of diameters, and number of trees.

Inventory-prediction equations developed to describe snowpack dynamics throughout the accumulation period showed similar statistical
form, except as possibly attributable to different precipitation inputs. Equations for characterizing residual snowpacks during spring runoff were statistically weak, possibly because factors other than those considered in this study control the runoff process.

The inventory-prediction equations were developed to estimate the mean snowpack water content on a basin, and to describe the trade-off, or the rate of exchange, between snowpack water content and forest-site variables on a decision-making unit. The equations do not necessarily predict changes in recoverable water yield resulting from the implementation of a land management system, however. Nonbiotic characteristics of the land, i.e., topographic features, geologic formations, and soil properties, could conceivably control water yield to the extent that changes predicted by the inventory-prediction equations could be masked.

Because of limitations in predicting potential changes in recoverable water yield, it was assumed that a land management system that maximizes snowpack water content on site would also provide the maximum potential for increasing recoverable water yield derived from snow. Management guidelines designed to allow snowpack water content to be maximized on site can be formulated within the framework of the inventory-prediction equations, multiple use management constraints, and forest-based product benefits and costs.

Management guidelines indicate that the greatest gain in snowpack water content on site would be realized on decision-making units where
the greatest reduction in forest cover density could be prescribed. However, a timber production constraint may limit the array of management possibilities. This constraint was defined as 35 to 40 square feet of basal area or 1,050 to 1,175 cubic feet of volume per acre, depending upon the existing growth percent and the intermingling of tree volumes and size classes. The potential increase in snowpack water content on site will be determined by the magnitude of the reduction in forest cover density and how close management re-direction can approach the timber production constraint. The proportion of the snowpack water content on site converted to recoverable water yield is dependent upon the runoff efficiency.
INTRODUCTION

In Arizona, a state with water supplies that could adversely affect aspects of future physical and economic development, less than ten percent of the average annual precipitation is recovered for the use of man (Barr et al. 1956, Mann 1963). A large portion of the recoverable precipitation is derived from forest covered mountains transversing the state from northwest to southeast. 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 efficiencies of watershed runoff can be increased.

The potential to increase the portion of recoverable water from Arizona forest lands appears to be greater for snow than for liquid rainfall. Sixty percent of the annual runoff in the Salt River basin occurs between January and April, much of it originating as snow, while runoff in the Verde River basin is 65 percent during the same period (Harshbarger et al. 1966). In the ponderosa pine (Pinus ponderosa Laws.) type, the most extensive forest type in the mountains of Arizona (Shupe, 1965, Spencer 1966, Wilson and Spencer 1967) yielding snowpack runoff, it has been observed that 99 percent of the annual water yield can occur between November and April, much of it originating as snow (Hansen and Ffolliott 1968). The mixed-conifer and spruce-fir types,
occurring at high elevations, may yield more runoff from snowpacks per unit area, but these vegetation types are of limited extent compared to the ponderosa pine type.

Studies indicate that the amount of snow reaching the ground surface and the portion of the snowpack that ultimately forms may be increased by changing the distribution of the snowpack on the ground and altering snow melt rates. Initial evidence (Anderson 1963, Baldwin 1957, Berndt 1961, Connaughton 1935, Dunford and Niederhof 1944, Gary and Coltharp 1967, Haupt 1951, Kittredge 1953, Lull and Rushmore 1960, Martinelli 1964, Maule 1934, Ozoga 1968, Packer 1962, Rothacher 1965, Weitzman and Bay 1959) indicates that these two snow management objectives can be accomplished by changing the structure, composition, and distribution of forest cover. More study of the relevant hydrologic principles and potentials is required, however.

The potential for forest-snow management in Arizona has been recognized by many, and, as a consequence, water yield improvement programs have been recommended (Barr et al. 1956, Mann 1963) and initiated on an experimental basis (Brown 1969a, Meyer 1967, Pase and Fogel 1967, Price 1967, Rich, Reynolds, West 1961, Rich 1965, Rich 1968, Worley 1965). Currently, pressures are being exerted on upstream land management agencies to implement operational water improvement action programs as soon as possible. These programs could involve
sweeping modifications of vegetation cover on lands where increased water yields might be expected. Some of these programs could jeopardize other land values, and many are irrevocable, at least in the short run (Worley and Miller 1964, Worley 1966). Furthermore, at the current level of knowledge, operational water improvement action programs cannot always be well defined or prescribed in terms of what must be sacrificed for expected increases in water yields. Nonetheless, upstream land managers often are required to make decisions now, and these management decisions may be made without complete guidelines.

Therefore, increased knowledge of forest-snow interactions is required before operational water improvement action programs can proceed with impunity. One of the first steps should be the recognition of hydrologic potentials (Anderson 1967a) in terms of snowpack dynamics as related to water yields within forest types. This is considered to be prerequisite to the formulation of effective and efficient programs.
DESCRIPTION OF THE STUDY

The development of inventory-prediction techniques that will describe snowpack dynamics as related to water yields within the ponderosa pine type in Arizona is suggested as an initial step in identifying comparative forest-snow hydrologic potentials. Direct snowpack measurements are impractical, with estimates of water yields synthesized from studies defining factors related to snowpack dynamics being the alternative. These studies need to provide data in the form required to express water yield potentials in terms suited for land management decision-making. For efficiency, snowpack inventory-prediction techniques should be compatible with inventories used to describe other forest-based products, i.e., timber, range, wildlife, etc. Also, the specific inventory-prediction techniques used to describe snowpack dynamics should be developed from input data that are either readily available or easily obtained by the land manager. This could conceivably insure wider acceptance and application of the techniques.

Studies that empirically relate snowpack dynamics to timber, topographic, climatic, and edaphic parameters with primary recognition of hydrologic principles need to be encouraged. Inventory-prediction systems could then be constructed within the context of these studies,

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allowing estimates of snowpack water yield potentials to be made. These estimates could be used to describe existing water improvement potentials and to define "optimum situations" that could subsequently become land management goals.

Controlled cause-and-effect investigations of detailed forest-snow interactions, while certainly to be preferred, can not always be satisfactorily executed because of incomplete knowledge, which is the current situation here. Pressures exerted on upstream land management agencies to implement operational water improvement programs as soon as possible requires action, however. Consequently, as an alternative methodology, the empirical approach was selected for use in the study described herein. The theoretical approach should receive priority consideration; but, interim empirical studies are suggested to identify and formulate efficient cause-and-effect relationships that can be applied now. The parameters selected for evaluation in the development of empirical relationships described below are considered potentially significant in obtaining knowledge of forest-snow interactions.

Objectives

Accepting the hypothesis that snowpack water yield is a primary source of recoverable water in Arizona, and that the potential for increasing recoverable snowpack water yields through forest-snow management appears to be greatest in the ponderosa pine type, this study was
designed to provide information necessary to satisfy the following general objectives:

1. Develop empirical inventory-prediction data and equations describing relationships between snowpack dynamics and inventory input variables, such as forest cover density, potential radiation, elevation, etc., common to the ponderosa pine type in Arizona.

2. Describe forest-snow prediction techniques and management guidelines applicable to the ponderosa pine type, and outline the implications of the data developed in this study as applied to resource-oriented multiple use land management.

Study Areas

Data necessary to satisfy the above objectives were obtained primarily from study areas on the Apache National Forest, near the Campbell Blue drainage, and on the Beaver Creek watershed, located on the Coconino National Forest (Figure 1). Cutover ponderosa pine characterize these study areas, and represents the range of timer overstory density conditions, size class intermixtures, and volume distributions common to extensive areas in the ponderosa pine type of Arizona.

Data were also obtained from a selected subsample of U. S. Soil Conservation Service (S.C.S.) Cooperative Snow Survey plots located in the ponderosa pine type (Figure 1). Although limited in terms of
Figure 1. Location of the Campbell Blue Plots, the Beaver Creek Plots, and the Subsample of S.C.S. Cooperative Snow Survey Plots
timber overstory variability, this subsample permitted an evaluation of forest-snow relationships as affected by year-to-year climatic variability.

Campbell Blue Plots

The Campbell Blue plots are located approximately seven miles south of Alpine, Arizona, on the Alpine Ranger District of the Apache National Forest. Ponderosa pine, comprising over 95 percent of the tree cover on the area, is essentially uneven-aged, with different age classes occurring either as small, uniform even-aged groups or as two or more even-aged groups in intermixture. Gambel oak (Quercus gambelii Nutt.) and quaking aspen (Populus tremuloides Michx.) are scattered minor species. Timber was last cut in 1966-67, with an estimated 40 percent of the merchantable sawtimber volume removed. Currently, ponderosa pine averages 415 stems, 95 square feet of basal area, and 1,975 cubic feet (Myers 1963a) of volume per acre. The estimated site index is 65 feet (Meyer 1961) or 70 feet (Minor 1964) at 100 years, depending on the basis.

Gently rolling topography with few slopes exceeding 15 percent characterize the study area. The mean elevation is 8,010 feet, with a limited range of 100 feet variation. Soils are derived from volcanics.

Annual precipitation on the Castle Creek watersheds, five miles south of the Campbell Blue plots, averages 27 inches, almost half of
which occurs between October 1 and May 31 (Rich 1968). Winter precipitation between November 15, 1968 and April 15, 1969, the sampling period on this study area, was 7.6 inches, which appears slightly below normal when compared with yearly precipitation records for the same period from nearby Alpine, Arizona (Figure 2).

Beaver Creek Plots

The Beaver Creek plots, located on the Beaver Creek Watershed Evaluation Project (Worley 1965, Price 1967, Brown 1969b), are 35 miles south-southeast of Flagstaff, Arizona, on the Long Valley Ranger District of the Coconino National Forest. Ponderosa pine comprises over 85 percent of the tree cover and, as on the Campbell Blue plots, is uneven-aged. Gambel oak and alligator juniper (Juniperus deppeana Steud.) occur as minor intermingling species. Timber was last harvested during a period from 1943 to 1950, when one-half of the merchantable volume of sawtimber was removed. Current ponderosa pine timber statistics include averages of 480 stems, 105 square feet of basal area, and 1,900 cubic feet (Myers 1963a) of volume per acre. The estimated site index is 70 feet (Meyer 1961) or 75 feet (Minor 1964) at 100 years, again, depending on the basis.

Topography varies on the study area from essentially level areas to slopes in excess of 45 percent. Elevation ranges from 7,325 to 7,725 feet. The soils, derived from volcanics, principally basalt with an
Figure 2. Mass Diagram Illustrating Winter Precipitation Patterns at Alpine, Arizona, near the Campbell Blue Plots
intermixture of cinders, are classified into the Brol liar and Siesta-Sponseller soil management areas (Williams and Anderson 1967).

Annual precipitation on the Beaver Creek watershed averages 24 inches, half of which occurs between November 15 and April 15. Winter precipitation between November 15 and April 15 for 1967-68 and 1968-69, the two sampling periods on this study area, was 18.8 and 19.9 inches, respectively. These values indicate above normal precipitation when compared with yearly records for the same period from Beaver Creek (Figure 3). The precipitation distribution patterns differ between the sampling periods, however, primarily as a result of record snowfall in December 1967 (Enz 1968).

S.C.S. Cooperative Snow Survey Plots

S.C.S. Cooperative Snow Surveys are designed specifically for purposes of snowmelt water yield forecasting for downstream reservoir management. As a prerequisite, the snow courses that provide the basic data in these surveys must be located where the snowpack is expected to persist throughout the forecasting period, essentially January 15 to April 15. Consequently, many courses are established in natural timber openings leeward to existing stands or in cienegas and parks; however, some courses have been placed within standing timber. Snow courses located in ponderosa pine timber stands were selected for study here.
Figure 3. Mass Diagram Illustrating Winter Precipitation Patterns on the Beaver Creek Watershed (Courtesy USFS)
Ponderosa pine dominates the timber overstory surrounding the snow courses selected for study, with Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), quaking aspen, Gambel oak, and alligator juniper minor stand components, their occurrence depending on local elevation and topographic positions. Ponderosa pine is sparse, representing primarily open old-growth or understocked young-growth stands. Average timber statistics are of little meaning, as these snow courses were not necessarily located to provide a sample of ponderosa pine density conditions.

Topography varies, although individual courses normally were uniform, with slopes rarely exceeding 25 percent. Elevations coincided with the range commonly associated with ponderosa pine in Arizona (Spencer 1966), 6,000 to 8,100 feet.

Precipitation input records are not consistently maintained for all snow courses, preventing detailed characterization and evaluation of yearly precipitation patterns.

**Field Procedures**

Large numbers of test variables are often available for consideration in empirical studies. A screening of variables may be necessary, therefore, selecting only those most rational in terms of satisfying the study objectives. Such was the case here. To facilitate the selection of variables for field measurement, a conceptual model relating snowpack dynamics to inventory-prediction data was developed as a study framework.
It was hypothesized that the snowpack water content at a point in time and space could be expressed as a function of precipitation, forest cover, and site. This model was formulated as follows:

\[ Y = f(P, FC, S) \]

where \( Y \) is snowpack water content at a point in time and space.

\( P \) is a measure of precipitation input.

\( FC \) is an expression of the spatial arrangement and density of the forest cover.

\( S \) is a composite expression of site, i.e., slope and aspect, elevation, soil, etc.

Using this model as a guideline, field procedures and methods were formulated with the underlying requirements to yield information necessary to quantify the model.

**Sampling Designs**

Two basic sampling designs were used as a basis for collecting data necessary to satisfy the study objectives.

The sample plot design on Campbell Blue and Beaver Creek consisted of a cluster of five sample points arranged in a diamond-shaped pattern within a circular 1/5-acre location (Figure 4). This sample plot design was selected, in part, to coordinate the efforts of this study with attempts by the U. S. Forest Service to develop aerial photo methods of
Figure 4. Distribution of Five Sample Plots Comprising the Primary Sampling Unit on the Campbell Blue and Beaver Creek Plots
of estimating snowpack accumulation and melt dynamics in the ponderosa pine type (Brown, Avery, Moessner 1967). In this latter study, a circular 1/5-acre aerial photo plot had been specified as the primary sampling unit, used principally to characterize forest crown cover.

Although similar in internal design, the general philosophy of sample plot location differed between Campbell Blue and Beaver Creek, reflecting divergent underlying study objectives. On Campbell Blue, it was desired to develop basic relationships describing snowpack dynamics in terms of inventory-prediction data obtained on the ground. This was considered prerequisite to, and separate from, the development of extensive inventory systems. Conversely, the objective of the sample plot location on Beaver Creek was to yield data applicable to the development of aerial photo inventory systems, not necessarily to include ground measurements as an intermediate step. Consequently, individual sample plots established on Campbell Blue were subjectively located in situations considered representative of the forest cover and site juxtaposition commonly encountered in the ponderosa pine type, as judged from the ground. It was felt that relationships developed from these plots could subsequently lend themselves to inventory-prediction synthesis. The Beaver Creek sample plots, on the other hand, were objectively located on aerial photos with respect to predetermined aerial photo forest cover and site strata thought representative of the ponderosa pine type, and
then established on the ground. It was assumed that relationships between snowpack dynamics and aerial photo parameters developed from these plots could be incorporated directly into inventory systems. The development of relationships between snowpack dynamics and ground measurements of forest cover and site received secondary consideration in selecting plot locations on Beaver Creek. The net effect of the differing philosophies of sample plot location was that individual plots on Campbell Blue were more frequently established in uniform forest cover and site conditions, as viewed from the ground, than the plots on Beaver Creek.

Forty sample plots were installed on the Campbell Blue study area, and 75 were located on Beaver Creek. Each plot was considered a primary sampling unit.

The snow courses utilized in the S.C.S. Cooperative Snow Surveys are basically a series of individual sample points located at constant intervals within relatively homogeneous forest cover and site conditions. The number of sample points on a course and the intervals between them are variable. In the subsample selected for evaluation here, eight to twelve sample points at 50-foot intervals was the most common sample design, although a design of as few as five points at 25-foot intervals was encountered (Figure 5). Since these snow courses were subjectively established in locations where the snowpack is
Figure 5. Distribution of Sample Points Comprising the Primary Sampling Unit on the Beaver Head (Upper-Right) and White Spar (Lower-Left) S.C.S. Cooperative Snow Survey Plots
expected to persist throughout the winter, they are not considered an unbiased sample of forest cover and site conditions occurring in the ponderosa pine type.

Eighteen snow courses were selected for evaluation in this study.

Snowpack Measurements

Water content (WE) measurements of the snowpack, which became the basic dependent variable in the study, were made with a snow tube and scale at all sample points. No attempt was made to differentiate between "new" and "old" snow as indicative of storm chronologies. The total water content at a sample point was the measurement objective.

Snowpack measurements were made during 1968-69 on Campbell Blue, and during 1967-68 and 1968-69 on Beaver Creek. On both study areas and for both field seasons, measurements were scheduled, insofar as possible, to characterize the following snowpack conditions:

1. Winter accumulation-melt period.
2. Peak accumulation, prior to spring runoff.
3. Spring runoff.
4. Residual snowpack at the end of spring runoff.

Measurements on the S.C.S. Cooperative Snow Survey plots are made on a regular bi-monthly schedule, specified by the Survey, starting January 15 and extending through April 15. Of these measurements, the maximum accumulation measured between January 1 and March 1 and
between March 1 and April 15 were arbitrarily selected for study. It was assumed that, in the average year, maximum accumulation in the first interval would index the winter accumulation-melt period, while maximum accumulation in the second interval, usually greater than the first, would represent the seasonal peak. Occasionally the reverse was true, in which case the greatest accumulation was considered the seasonal peak and the second measurement omitted from analyses.

Measurements have been obtained on these snow courses for a variable number of years, depending on the installation date. Up to 35 years of record are available from the older courses, with five years from the most recently installed. All available data were utilized in the study analyses because of the need to evaluate between-year variations in snowpack behavior, which is limited with short-term studies.

Forest Cover Measurements

Of the components in the model providing a conceptual framework for this study, forest cover is the only variable that can be manipulated in the water improvement programs currently being considered for implementation in Arizona. Consequently, forest cover variables received priority consideration in the development of inventory-prediction data relating snowpack dynamics to inventory input variables.

Unfortunately, the processes influencing the snowpack dynamics have been better described than evaluated. Separating the effect of the
forest on interception, shading, shelter from winds, and radiation phenomena has been frustrated by the fact that the same trees and the same part of a single tree can be acting on several processes simultaneously (Anderson 1967b). It is particularly difficult to separate the different processes influencing snowpack dynamics in empirical studies. However, it may be possible to index some of the processes, either directly, indirectly, or in interaction with other processes. This was the objective here. Those processes of prime interest, and conceivably indexed by different measurements of forest cover, were interception of precipitation inputs, obstruction of direct beam solar radiation, and re-radiation from trees onto the snowpack.

The forest cover variables described below are measurements of density, as opposed to measurements of stocking. Stocking and density have often been applied interchangeably, and this usage has often resulted in confusion (Avery 1967, Bickford 1957, Gingrich 1965). Stocking is a qualitative term, referring to the degree of adequacy of a forest in meeting a management objective. A forest may be well stocked or poorly stocked depending on comparison of existing conditions with conditions desired for optimum forest growth and volume. Conceivably, with increased knowledge of forest-snow interactions as related to water yields, forests may eventually be described as well stocked or poorly stocked with reference to specific forest-snow management objectives.
In contrast, density is a quantitative term, expressing the extent of forest crowding within a stocked area. Density usually reflects some combination of tree diameter, height, number of trees, or form, and it is normally expressed on a per acre basis.

**Point Sampling Methods.** The forest cover variables considered in this study were developed from point sampling techniques, employing standard mensurational procedures. Point sampling techniques are widely used in forest inventories (Beers and Miller 1964, Bell and Alexander 1957, Grosenbaugh 1952, Grosenbaugh 1958, Hovind and Rieck 1961, Kulow 1965, Morrow 1958, Orr 1959), providing descriptions of forests for management purposes. The theory, synthesis, and geometric implications behind point sampling will not be detailed here, but numerous references on the subject are available (Laban 1967, Thomson and Deitschman 1959).

The advantages of point sampling vis-a-vis fixed-area plot sampling have been well documented (Dilworth and Bell 1968, Shain and Rudolph 1965). Generally, the advantages include increased speed of sampling, greater efficiency in field work, ease of identifying trees in the sample, and a better balance between trees of large and small diameter. Expressions of forest density developed by point sampling are considered basically identical to expressions of density developed from measurements obtained by fixed-area plot sampling (Borgeson, Colcough,

Point sampling consists of selecting trees for tally whose diameters are equal to or greater than a series of predetermined fixed angles whose vertex are at the sample point (Figure 6). The fixed angles are defined by an angle gage (Grosenbaugh 1955, Kulow 1965) corresponding to basal area factors. Basal area factors specify the number of square feet of basal area contributed by each tree tallied in a sample.

The inclusion of a tree in a sample tally is dependent upon its diameter, distance from the sample point, and the basal area factor used. With small basal area factors defining small angles, more trees at greater distances from the sample point are sampled than with large basal area factors which define large angles. Regardless of diameter, location, or basal area factor, all trees tallied can be put on a per acre basis following standard point sampling analytic procedures (Barrett 1969, Dilworth and Bell 1968, Grosenbaugh 1958), allowing computations of basal area, number of trees, and volume per acre to be made.

Using a basal area factor of 25 to select sample trees, the average tally from the five sample point cluster comprising the primary sampling units on Campbell Blue and Beaver Creek generally provided the basis for the development of the forest cover variables. Average tallies and, occasionally, individual sample plot tallies were the basis for the
Figure 6. How Point Sampling Works in the Field. A tree is selected for tally whose diameter is equal to or greater than a pre-determined fixed angle whose vertex is at sample point (Grosenbaugh 1952)
development of forest cover variables on the snow courses in the S.C.S. Cooperative Snow Surveys.

Additionally, basal area factors of 25, 50, 75, and 100 were used to select sample trees at individual sample points to describe discrete patterns of forest cover.

**Basal Area.** One of the more widely accepted expressions of forest density in the United States is basal area, defined as the total cross-sectional area of all tree boles on a unit area, usually an acre, measured in square feet at 4-1/2 feet above the ground. Although not always adequately indicating size class distribution patterns, particularly in uneven-aged forests (Howard, 1957), basal area is an objective measure of forest density, and it is easily understood by land managers. Furthermore, basal area is easily determined in the field, readily converted to other forest density expressions (Avery 1967, Minor 1961), and many multiple use relations have already been developed with basal area as the independent variable (Aldon 1968, Gaines and Kotok 1954, Orr 1968, Pase and Hurd 1957, Reynolds 1969).

The primary reason for measuring basal area is that it is assumed to index forest crown cover, which, in turn, affects all three of the processes influencing snowpack dynamics considered in this study. Essentially, the greater the extent and mass of the crown cover, the greater is the potential for interception of precipitation, which may or
may not result in net losses in snow accumulation. Also, the greater the crown cover, the greater is the obstacle to direct beam solar radiation, and the greater is the tree mass available for re-radiation onto the snowpack, both of which may affect energy supplies required for snow melt (Anderson 1956, Miller 1966, Packer 1962, Reifsnyder and Lull 1965, Satterlund and Eschner 1965, Satterlund and Haupt 1967, Vezina and Pech 1964).

Aerial photo interpreters assume that basal area is proportional to forest crown cover, as estimated from aerial photos. This has led to the development of indices between estimates of crown cover derived from aerial photos and basal area (Moessner 1965). It is possible, however, that a more sensitive measure of crown cover as it may influence snowpack dynamics can be developed from canopy photos (Brown 1962) obtained from ground camera points. Canopy photos can be used to determine varied information about the forest overstory surrounding the camera point (Brown and Worley 1965). The extent of crown cover affecting different overhead areas is one such use.

In an exploratory investigation in Arizona (Garn 1969), forest crown cover affecting an overhead area of 90 degrees, delineated by an angle of 45 degrees from the horizon (Figure 7), has been shown to be a statistically significant variable in empirical equations describing the total depth of the snowpack. Consequently, this measure of crown cover was used in the current study.
Figure 7. Schematic (a) Showing Top View of Overhead Area of 90 Degrees and (b) Hemisphere Delineated by an Angle of 45 Degrees from Horizon (Garn 1969)
It was impractical to take the number of canopy photos required to measure crown cover on all of the sample points in this study. It seemed even more impractical to take canopy photos for use in extensive inventories. An alternative method was to index crown cover with expressions of basal area estimated by point sampling techniques. This general approach has been applied previously (Adams 1962), using measurements of crown cover obtained from the hemispherical photo-canopymeter (Clark 1961).

In point sampling, the basal area factor to use in determining the density conditions associated with crown cover depends, theoretically upon the overhead areas. Crown cones affecting large overhead areas, cones of 180, 120 degrees, etc., involves trees further from the camera point than does crown cover for smaller overhead areas. Similarly, smaller basal area factors tally trees further from the sample point than do larger basal area factors. Consequently, an inverse relationship would be expected, i.e., as the overhead area becomes smaller, the basal area factor most appropriate for measuring associated basal area becomes larger.

An overhead area of 90 degrees, by geometry, means that all trees within approximately one tree-height in distance from the camera point would contribute to crown cover. It was hypothesized, therefore, that smaller basal area factors would better sample trees within this distance. Larger basal area factors, where only those trees very close
to the point would be tallied, would tend to omit too many.

A supplementary investigation was carried out to determine which of the basal area factors used in this study, 25, 50, 75, or 100, were most closely correlated with forest crown cover affecting the specified overhead area of 90 degrees. The results indicated that all basal area factors with the exception of 100 could be employed. However, to include the maximum number of sample trees in the tally, a mensurational prerequisite for the development of subsequent expressions of forest density, a basal area factor of 25 was selected as a base.

Point sampling is essentially based on the theory that each tree tallied, regardless of its diameter, represents the same basal area, that corresponding to the basal area factor used in sampling. Therefore, each tree tallied at a sample point multiplied by 25, the basal area factor, gave the estimated basal area at the sample point. The estimated basal area at a primary sampling unit, whether Campbell Blue, Beaver Creek, or the snow courses in the S.C.S. Cooperative Snow Surveys, was obtained by multiplying the average tree tally at each point in the sampling unit by 25.

Diameters of all tally trees were recorded to allow subsequent assignment into timber size classes for the development of other expressions of forest density.

**Point Density.** It seemed possible that a more sensitive measure of basal area density at an individual sample point could better relate
to snowpack dynamics, primarily because snowpack water content measurements made in this study were on a point basis. Consequently, the angle-summation method (Gerrard 1969, Spurr 1962) of computing basal area at individual sample points was evaluated on a subsample of 30 points on the Campbell Blue and Beaver Creek study areas to test this supposition.

Angle-summation involves the measurement of the actual angle subtended by trees surrounding a point rather than counting the number of trees equal to or exceeding a predetermined fixed angle, the procedure followed with the angle-count method. An angle-count determined by rotating an angle gage around a sample point indicates the number of trees equal to or exceeding a fixed angle, but it does not show by how much they exceed the angle or where they are distributed with respect to the point. Large trees within the immediate vicinity of the point can give the same angle-count as an equal number of trees at the periphery of a wide circle. However, the larger trees nearer the sample point seemingly exert a greater influence upon the point.

In angle-summation, an angle is chosen to delineate a 1-tree plot and an estimate of basal area is made, then a second angle is chosen to establish a 2-tree plot and a second estimate of basal area is made, etc., until the number of trees specified have been measured.

The 1-tree plot is based upon that tree subtending the largest angle with the sample point as the vertex, although the tree selected
need not necessarily be the closest or largest in the vicinity. For a 2-tree plot, the tree subtending the second largest angle is selected for measurement. Again, this tree need not be the second closest or the second largest. All of the basal areas of the first tree, that tallied for the 1-tree plot, falls within the new plot, but only half the basal area of the second tree does. This procedure is repeated until the desired number of trees, here, arbitrarily specified as five, has been measured.

In accordance with the theory of point sampling, for a \textit{n}th tree plot, basal area in square feet per acre is approximated by the following formula (Spurr 1962):

\[
BA = \frac{75.625}{n} \sum_{k=1}^{n} (k-1) \left( \frac{D_k}{L_k} \right)^2
\]

where \( BA \) is the mean basal area for an estimate based upon \( n \) measured trees.

\( n \) is the number of trees measured.

\( D \) is the diameter of the \( n \)th tree, in inches.

\( L \) is the distance from the center of the \( n \)th tree to the sample point, in feet.

Application of the above formula to the five tree measurements made at each point in the subsample yielded five estimates of mean basal area. These estimates then became the basis for evaluating point density in terms of snowpack dynamics.
Sum of Diameters. The sum of tree diameters, defined as the summation of diameters on a unit area measured in inches 4-1/2 feet above the ground, is a measure of forest density similar to basal area. However, because the sum of diameters gives more weight to smaller trees relative to larger trees, it is not directly correlated with basal area, especially in uneven-aged forests comprised of many size classes. Consequently, as the basic structure of the ponderosa pine type in Arizona is essentially uneven-aged, it was considered here as a possible alternative to basal area for indexing forest crown cover.

Being another index of crown cover, the sum of diameters was assumed to relate to snowpack dynamics in a manner similar to basal area, generally acting through the processes of interception of precipitation inputs, obstruction of direct beam solar radiation, and re-radiation from trees onto the snowpack. In particular, the sum of diameters has been shown (Eschner and Satterlund 1963, Wellner 1948) to be a good indicator of the estimated transmission of direct beam solar radiation through forest canopies.

Expressions of sums of diameters per acre on a primary sampling unit basis were synthesized from the trees selected for basal area measurement on the Campbell Blue and Beaver Creek study areas. The diameter of these sample trees formed the computational base.

Number of Trees. Perhaps the most logical measure of forest density is simply the number of trees occurring on a unit area.
Unfortunately, unless coupled with some indication of tree size, spacing, or distribution, this expression of density can be of little mensurational value or meaning (Avery 1967, Bickford 1957, Davis 1954). However, number of trees was considered a potential snowpack inventory-prediction variable here because it was assumed to be another measure of crown cover, and, consequently, another index of the different processes influencing snowpack dynamics, and because of its relative ease of determination and interpretation.

Number of trees per acre on a primary sampling unit basis was determined by expanding the tally of trees selected for basal area measurement on Campbell Blue and Beaver Creek to per acre values following standard point sampling procedures (Barrett 1969, Grosenbaugh 1958).

**Bole Area.** The surface area of the main stem of individual trees, termed bole area, has been suggested as a measure of forest density (Bickford 1957, Davis 1954, Lexen 1943). Bole area, which is roughly equivalent to the cambium area, is a measure of the actual growing surface which produces merchantable woods. Therefore, it was originally proposed as an expression of growing stock density for silvicultural purposes (Lexen 1943). In this study, however, bole area was considered to be a measure of tree stem surface area absorbing short-wave radiation from the atmosphere and re-radiating
long-wave radiation onto the snowpack (Lull and Reigner 1967, Miller 1955, Reifsnyder and Lull 1965).

Bole area, being a measure of forest density, is correlated with basal area, sum of diameters, and number of trees. Consequently, it can be considered an index of crown cover. But, because bole area provides a direct estimate of the surface area of tree stems, its primary value as a snowpack inventory-prediction variable could be in indexing surfaces of potential energy transfers that occur below the general forest crown canopy level. Conceptually, this latter index could become dominant, as opposed to an index of crown cover, in dense forests of trees characterized by small, sparse crowns relative to total tree height. Unfortunately, the significance of these two indices, crown cover vis-a-vis surface area of tree stems, could be evaluated separately in this study.

Logarithmic formulae describing the bole area of individual trees as a function of diameter and height have been developed for ponderosa pine (Lexen 1943). Approximations to these formulae, suggested because of the proximity of the exponents to unity, were employed here to develop estimates of bole area.

The values for bole areas of immature ponderosa pine, trees generally less than 20 inches in diameter, can be approximated from the following expression:
\[
BO = \frac{(D)(H)}{7.2}
\]

where \(BO\) is the bole area of an individual tree, in square feet.

\(D\) is tree diameter, in inches.

\(H\) is total tree height, in feet.

For mature ponderosa pine, trees at least 20 inches in diameter, bole area can be approximated as follows:

\[
BO = \frac{(D)(H)}{6.6}
\]

Bole area per acre on a primary sampling unit basis was obtained by applying the above approximations to the per acre expansions of trees selected for measurement of basal area on Campbell Blue and Beaver Creek. The diameter and total height of these sample trees provided the computational base.

**Volume.** Diameter, height, and tree form, considered together, yields volume, the most obvious measure of forest density (Avery 1967, Bickford 1957, Davis 1954). Ultimately, forest density must be expressed in terms of volume for purposes of economic evaluation. This was the primary reason for considering it in this study. Also, being a measure of forest density, volume conceivable provides an estimate of crown cover.
In order to develop efficient forest-snow management guidelines, the possibilities for altering snowpack water yields need to be contrasted to changes in other forest-based products. Priority considerations should be given to timber products, primarily because this is the resource that will probably be manipulated in the initial implementation of water yield improvement programs. For flexibility in the interpretation of multi-product timber changes, a necessity with dynamic wood utilization and market conditions, cubic foot volume was selected as the basic unit of volume measurement. Cubic foot volume gives the closest approximation to the true multi-product potential of all trees of any diameter and height class. Furthermore, cubic foot volume can readily be converted into other specific timber product measurement units (Forbes 1955).

Estimates of cubic foot volume per acre on a primary sampling unit basis were developed by applying ponderosa pine point sampling volume table values (Myers 1963b) to the trees selected for basal area measurement on Campbell Blue and Beaver Creek. Again, the diameters and total height of these sample trees formed the computational base.

**Number of Trees in Relation to Height.** All of the above expressions of forest density utilize tree diameter as an integral unit. The probability of a tree being included in the sample was directly proportional to its diameter (Beers and Miller 1965, Grosenbaugh 1958, Hovind
and Rieck 1961). Consequently, to complete a study of alternative measures of the spatial distribution and density of forest cover as these measurements may affect snowpack dynamics, an expression of density based on the number of trees in relation only to height was evaluated. The mensurational merit of such an expression of density is that height, especially of dominants and codominants in crown position, is considered comparatively insensitive to density except, possibly, at the extremes (Bickford 1957, Briegleb 1952, Davis 1954, Gevorkianz 1947, Wilson 1943). This expression, therefore, is based on an independent factor, height, rather than diameter, a correlated resultant of density.

It is difficult to conceptually rationalize an inventory-prediction variable based only on tree height in terms of how it may relate to processes influencing snowpack dynamics. Being another expression of density, it can be assumed to be a measure of forest biomass, and consequently, to index interception of precipitation inputs, obstruction of direct beam solar radiation, and re-radiation from trees onto the snowpack. Unfortunately, however, the linkage between a height-based measure of density and these processes is not currently as clearly understood as with measurements of forest density based principally on diameter. Justification for considering it here is that the number of trees in relation to height is a consistent and
objective measure of density. Therefore, such a measure should be investigated with respect to influencing snowpack accumulation and melt.

The number of trees per acre for uniformly stocked, even-aged forests of any species composition can be related to tree height through application of the following formula (Davis 1954, Wilson 1943):

\[
N = \frac{43,560}{(H\cdot f)^2}
\]

where \(N\) is the number of trees per acre.

43,560 is the number of square feet in an acre.

\(H\) is the mean height of the forest, in feet.

\(f\) is a fraction of the height (\(H\)) that expresses the spacing between trees considered to be appropriate for the species, as a decimal.

Thus, for example, for 60-foot trees and a 25 percent spacing factor, the number of trees per acre is

\[
N = \frac{43,560}{(15)^2} = 194
\]

Theoretical numbers of trees appropriate for a given species, height class, and spacing factor can be determined from the above formula. Then, by comparing theoretical numbers with actual numbers of trees as tallied on the ground, a height-index (Larson and Minor
1968) can be constructed, as follows:

\[ HI = \frac{N_a}{N_t} \]

where HI is the height-index value.

\( N_a \) is the actual number of trees per acre, determined from the tally of sample trees on the ground.

\( N_t \) is the theoretical number of trees per acre, calculated from the above formula using the mean height of the dominant and codominant sample trees and an appropriate spacing factor.

Height-index values equivalent to unity are assumed to be indicative of a density norm, defined as a forest of desirable form, structure, and distribution, on the basis of the designated spacing factor (Davis 1954). Height-index values less than unity are considered to represent too sparse conditions, while values exceeding unity represent too dense conditions.

Height-index values can only be developed for uniformly stocked, even-aged forests. Consequently, just those primary sampling units on Campbell Blue and Beaver Creek that approached this prerequisite could be considered for evaluation. A requirement that
at least 60 percent of the total number of trees tallied on a sampling unit had to be dominant or codominant in crown position was a rule of thumb imposed in deciding whether a unit qualified. Sampling units failing to meet this requirement were excluded from consideration.

Total height of the dominant and codominant trees selected for basal area measurement provided the computational basis for determining mean height. A spacing factor of 0.28 has been defined for the ponderosa pine type in Arizona (Larson 1968, Larson and Minor 1968), and it was considered appropriate for this study.

Additional Measurements of Forest Cover. Several additional measurements describing the spatial distribution and density of forest cover were originally scheduled for evaluation as potential snowpack inventory-prediction variables. These measurements included stand-density index (Avery 1967, Davis 1954, Reineke 1933), tree-area ratio (Christman and Schumacher 1940, Gingrich 1967), crown competition factor (Alexander, Tackle, and Dahms 1967, Krajicek, Brinkman, and Gingrich 1961), and stocking percentage (Lynch 1958). However, due to limitations in describing forest density conditions characteristic of the ponderosa pine type in Arizona, and because these measurements lend little additional mensurational sophistication to those variables already described above, they were omitted from detailed analyses after preliminary investigation.
Potential Direct Beam Solar Radiation

The water content of a snowpack at a point in time generally expresses an integrating effect of snow input accumulation and subsequent ablation. Considering just the latter phenomenon, snow ablation requires heat, the ultimate sources of which are derived partly or wholly from radiant energy (Reifsnyder and Lull 1965). Consequently, it appeared necessary to synthesize a readily obtainable radiant energy inventory-prediction variable to index the potential magnitude of energy elements available for melting snow on different sites.

It has been suggested (Megahan, Meiman, and Goodell 1967) that net allwave radiation would provide a reliable index of incremental snow melt on a watershed basis. However, because of an apparent dominant role played by direct beam solar radiation in the energy balance associated with forested areas, it seemed plausible to consider this one component as an index of snow melt. Direct beam solar radiation is but one of several components in the radiation balance, yet differences between areas are often assumed to be a function of this one parameter (Fons, Bruce, and McMasters 1960, Frank and Lee 1966). For example, a radiation balance may be formulated as follows:

\[ R_n = R_s + R_d + R_a - R_T - R_g \]

where \( R_n \) is the net radiation balance.

\( R_s \) is direct beam solar radiation.
\( R_d \) is diffuse sky radiation.

\( R_a \) is incoming thermal radiation from the atmosphere.

\( R_r \) is reflected radiation.

\( R_g \) is outgoing thermal radiation emitted from the surface.

Long-term measurements of the various components have indicated that \( R_d, R_a, R_r, \) and \( R_g \) are largely self-cancelling (Frank and Lee 1966), confirming the dominant role of direct beam solar radiation.

Solar radiation values can be computed from the solar constant, the turbidity factor, and the geometry of a local site with respect to the sun's rays (Frank and Lee 1966, Reifsnyder and Lull 1965). If the turbidity factor is ignored, a reasonable assumption for long-term considerations in the forested areas of Arizona, a theoretical parameter, termed potential direct beam solar radiation, can be synthesized. With this parameter, the direct beam solar radiation intensity on a site is proportional to the angle of incidence, which in turn is dependent on the latitude, time of day (hour angle), time of year (solar declination), and surface inclination and orientation.

Although potential may differ from actual direct beam solar radiation, the former provides a basis for indexing and comparing the radiant energy flux among local sites (Frank and Lee 1966). Furthermore, potential direct beam solar radiation, developed without
resorting to extensive instrumentation (Lull and Reigner 1967), also meets the requirements of being based on readily available or easily obtained information.

For a given locale, considering a solar day as the basic unit of time, potential direct beam solar radiation, in Langley's (gram calories cm\(^{-2}\)), can be obtained from tables (Frank and Lee 1966) with just slope percent and aspect measurements. This procedure was employed here, with average slope percent and aspect at each primary sampling unit and the tabled solar day closest to the date of snowpack water content measurement serving as the basis.

No attempt was made to evaluate or index other sources of heat potentially available for snow ablation, e.g., those components in the above radiation balance other than direct beam solar radiation. Measurement of these sources, although critical in developing a complete outline of the thermodynamics relating to snow melt (Wilson 1941), was considered beyond the scope and objectives of the present study.

Elevation

Greater amounts of snow generally accumulate at higher than lower elevations, indicating more snow inputs and lower temperatures at higher elevations. However, by itself, elevation may be a dangerous variable, often being poorly correlated with geology, soils,
vegetation, and climate (Lull and Anderson 1967). These latter hydrologic variables are reasonably homogeneous over the range in elevations encountered in this study, though, allowing elevation to be included in the snowpack inventory-prediction model evaluated.

Elevation could not be analyzed on the Campbell Blue study area because the maximum difference in elevation between primary sampling units was less than 100 feet. On Beaver Creek, where the range in elevations approach 500 feet, elevation at each sampling unit was estimated from 7-1/2 minute U. S. Geological Survey topographic maps with 20-foot contours. Elevation became part of the record with the establishment of the snow courses utilized in the S.C.S. Cooperative Snow Surveys, and these values were used to characterize these sampling units.

Soil

The inclusion of soil as a snowpack inventory-prediction variable was index different thermal conductivity (Wilson 1959) and infiltration capacity (Kittredge 1948) characteristics possibly related to the melting process. Detailed analyses of the physical properties of soil was not the objective here. Rather, the objective was to evaluate the above characteristics within the framework of existing soil descriptions available to the land manager.
Analysis of soil as a variable was confined to the Beaver Creek study area because of the current availability of soil descriptions and mappings (Williams and Anderson 1967). Each primary sampling unit on Beaver Creek was initially classified in terms of soil management area, a grouping of two or more soil types related to the shape of the land surface and the nature of the soil material. It was felt that subsequent classification breakdowns could be made as required.

Precipitation

One of the more obvious snowpack inventory-prediction variables warranting consideration is a measure of the magnitude of precipitation inputs. It seems reasonable to assume that a relatively close correlation should exist between total snow input and accumulated snowpack water content. The development of a snow input variable is necessary to describe snowpack water content at a point in time and space. Also, an evaluation of a snow input variable could yield insight into the interpretations of results obtained from short-term studies necessarily conditioned by the specific weather patterns encountered.

Year-to-year variations in precipitation patterns prevented the development of snow input variables on the Campbell Blue and Beaver Creek study areas, with but one year and two years of incoming precipitation and snowpack water content records available, respectively.
The only opportunity to evaluate and analyze snow input as an inventory-prediction variable in this study was with the precipitation and snowpack content records available from a subsample of snow courses utilized in the S.C.S. Cooperative Snow Surveys. Unfortunately, because of the procedure of establishing courses in areas where snow is expected to persist throughout the winter, the S.C.S. records may not necessarily be indicative of the full range of incoming precipitation and forest-site interactions common to the ponderosa pine type in Arizona. However, these data represent the only systematic, long-term record of any sample of these interactions. Consequently, it was felt that their consideration was justified.

**Analytic Procedures**

As stated previously, the field procedures discussed above were designed to provide input data necessary to quantify the conceptual model relating snowpack dynamics to inventory-prediction data that were formulated as a study framework. To analytically quantify this model, regression analyses (Ezekiel and Fox 1959, Freese 1964, Williams 1959) were employed.

Additional statistical techniques used in attempting to satisfy the general study objectives included analyses of variance (Freese 1967, Snedecor 1956, Steel and Torrie 1960) and, when appropriate, multiple comparison tests (Hamilton 1965). These procedures were used to
identify and evaluate snowpack water content differences between
discretely defined forest-site interactions.

Regression Analyses Methods

Generally, two approaches are open to investigators developing inventory-prediction regressions and formulae: (1) stepwise regression analyses, and (2) computation of all possible regression combinations (Furnival 1965, Gorman and Toman 1966). In the stepwise procedure, independent variables are added (or subtracted) one at a time according to their relative contributions to the regression equation. Once included in a regression, an independent variable is retained in all subsequent steps. This procedure has the disadvantage in that the best variables to use when two independent variables are included may not necessarily be the best when three independent variables are included, and so on. Another unsatisfactory feature of the stepwise procedure is that the single equation ultimately produced may not be the best equation in terms of a higher coefficient of determination or a lower sum of squares of residuals (Gorman and Toman 1966) than any other equation with the same number of independent variables. Also, given the "best" equation, it may still be necessary to know how subsequent predictions would change if variables in this equation were replaced by other variables easier to observe or cheaper to measure (Furnival 1965).
An alternative to the stepwise procedure is to compute all possible regression combinations, considering all combinations of dependent, if appropriate, and independent variables. This is a good procedure when the number of variables is small, but it can become impossible when the number of variables is large. The number of regressions computed in an all possible combinations analysis is \(2^n - 1\), where \(n\) is the number of independent variables. It is obvious that, as the number of independent variables becomes large, the time required to compute all possible regressions, even when utilizing a high-speed computer, becomes astronomical.

If computation of all possible regressions is selected as the analytic base, as it was here, a screening of potential variables can be carried out, attempting to reduce the number of regressions developed. Two options are open for solving screening problems: (1) use the stepwise procedure, or (2) restrict the regression combinations to combinations of independent variables which meet pre-determined constraints (Furnival 1965). The latter approach was selected here, with the following assumptions and constraints specified:

1. Forest cover and site variables are independent of each other, with all interactions considered statistically non-significant.

2. A forest cover independent variable must appear in every regression, this being the only variable class considered that can be manipulated in water improvement programs.
3. Only one expression of forest cover may appear in a single regression, as a high degree of correlation exists between the different expressions developed.

4. Algebraic and transcendental functions describing a single expression of forest cover will be acceptable, and more than one such function may appear in a single regression. It was assumed that, this being an exploratory empirical study, a regression equation including several functions describing a single forest cover variable was acceptable.

5. Site variables must assume linear functions with respect to the dependent variable. This constraint was verified through preliminary investigations.

Using ADP procedures, the following snowpack inventory-prediction relationships were defined:

(1) \( Y = f(X_1) \)

where \( Y \) is snowpack water content characterizing specified snowpack conditions.

\( X_1 \) is a forest cover variable, i.e., basal area, sum of diameters, number of trees, etc.

(2) \( Y = f(X_1, X_2) \)

where \( Y \) is as defined above.

\( X_1 \) is as defined above.
X₂ is potential direct beam solar radiation for tabled solar day (Frank and Lee 1966) closest to the date of snowpack measurements.

(3) Y = f(X₁, X₂, X₃)

where Y is as defined above.

X₁ is as defined above.

X₂ is as defined above.

X₃ is elevation.

To investigate the potential significance of the forest cover variables, the first relationship was evaluated in transformation detail (Ezekiel and Fox 1959, Freese 1964) as follows:

(1) Y = f(X₁), a linear model

(2) Y = f(1/X₁), a hyperbolic model.

(3) Y = f(X₁²), a parabolic model.

(4) Y = f(ln X₁), a logarithmic model.

Also, considering each of the above independent variables transformation functions as separate regression variables, the best combinations, in terms of correlation coefficients, with two independent variables, the best with three, and, finally, all four independent variables were determined.

For all regression formulae developed, the standard error of estimate (Sᵧₓ) and coefficient of determination (r²) were computed.
These statistics describe how closely snowpack water content can be estimated from the inventory-prediction variables and the amount of variance in snowpack water content associated with the different inventory-prediction variables, respectively. Knowledge of the standard error of estimate may also assist in pooling snowpack inventory-prediction regression variances with auxiliary inventory variances (Cochran 1963), a possible necessity for extensive applications.

An additional statistic (cp) was computed to assist in identifying the better snowpack inventory-prediction formulae. With this statistic, regression equations can be compared with respect to bias and random error (Gorman and Toman 1966), and the best candidate selected accordingly.

The $cp$ statistic is related to the total error of predicted values of $Y_i$ for all $N$ data points in a regression. Briefly, following the general derivation of Gorman and Toman (1966), the total squared error (bias plus random) for $N$ data points using a $p$ term (variable) regression equation is:

$$
\sum_{k=1}^{n} (y_i - n_i)^2 + \sum_{k=1}^{n} \text{Var} (Y_{pi})
$$

where $v_i$ is the expected value from the true equation.

$n_i$ is the expected value from the regression equation.
(v_i - n_i) is bias at the i-th data point, by definition (Gorman and Toman 1966).

Letting $SSB$ represent $\sum_{k=1}^{n} (v_i - n_i)^2$, the standardized total squared-error is defined as follows:

$$T_p = \frac{SSB}{S^2} + \frac{1}{S^2} \sum_{k=1}^{n} \text{Var}(Y_{pi})$$

where $T_p$ is the standardized total squared error.

$S^2$, is the population variance, as opposed to $s^2$, which is a sample estimate ($\hat{s}^2$) of the population variance.

It has been shown (Gorman and Toman 1966) that:

$$\sum_{k=1}^{n} \text{Var}(Y_{pi}) = pS^2$$

Therefore, substituting above gives:

$$T_p = \frac{SSB}{S^2} + p$$

The residual sum of square, RSS, from a $p$ term regression equation has expectation:

$$E(RSS) = SSB + (N-p)S^2$$

Solving for $SSB$,

$$SSB = E(RSS) - (N-p)S^2$$

Substituting above gives:
\[ T_p = \frac{E(RSS)}{S^2} - (N-p) + p \]
\[ = \frac{E(RSS)}{S^2} - (N-2p) \]

With an unbiased estimate of \( S^2 \), the \( cp \) statistic, by definition (Gorman and Toman 1966), is an estimate of the standardized total squared error (\( T_p \)):

\[ cp = \frac{RSS}{S^2} - (N-2p) \]

When a \( p \) term equation has negligible bias, SSB approaches zero, RSS estimates \( (N-p)S^2 \), and

\[ cp = \frac{(N-p)S^2}{S^2} - (N-2p) \]

However, it is assumed that \( \hat{S}^2 \) approaches \( S^2 \), so

\[ cp = (N-p) - (N-2p) = p \]

Graphically, if \( cp \) statistics for a number of regression equations are plotted against the number of variables in the equations (\( p \)), the \( cp \) values for equations with small bias will cluster about the line \( cp = p \) (Figure 8, points A, B, and C), while \( cp \) values for equations with bias will fall above the line (Figure 8, point D). Although a \( cp \) value may be above the line \( cp = p \) (Figure 8, point D), it may still be indicative of an equation with lower total error than an equation of more variables with a \( cp \) value on the line (Figure 8, point C). It is
Figure 8. A Plot of the $cp$ Statistic for a Number of Regression Equations against $p$ (The number of variables in the equation). Equations with small bias will cluster about the line $cp = p$ (Gorman and Toman 1966)
conceivable, therefore, that adding variables may reduce bias, but at the expense of increasing the total variance of prediction for the $N$ data points (Gorman and Toman 1966).

An unbiased estimate of the population variance is needed to calculate $cp$ values. The mean square residual error from the complete regression equation, all possible variables considered, serves this purpose (Gorman and Toman 1966), but this forces $cp = p$ for the complete equation. Therefore, to use this estimate of the population variance in the $cp$ calculations, it is assumed that the complete equation is representative of negligible bias.

An array of simple linear regression formulae predicting snowpack water content as a function of basal area determined by 1-, 2-, 3-, 4-, and 5-tree plots was developed to evaluate point density estimates of basal area. To analyze the relative merit of these regression formulae in terms of correlation between variables, the sums of squares for regression were tested (Baten 1941, Hotelling 1940, Williams 1959) for statistically significant differences.

Analyses of Variance

Analyses of variance were made to test for statistically significant differences between snowpack dynamics and discretely defined inventory-prediction parameters. These techniques were specifically employed to evaluate differences between snowpack dynamics and soil
management areas, determined on the Beaver Creek study area, and between snowpack water content and relative distances sample points occur from surrounding forest cover. This latter test was made to develop land management guidelines outlining patterns of forest cover as related to the snowpack.

Specific anovas constructed were single classification with unequal replications (Freese 1967, Snedecor 1956, Steel and Torrie 1960).

When significant differences did occur, Tukey's multiple comparison test was used to isolate differences between pairs of means. Tukey's test was selected because this method is sensitive to the experimentwise error rate (Hamilton 1965), which defines the proportion of experiments with one or more erroneous inferences when the null hypotheses are true. Furthermore, Tukey's test is valid no matter how the true means are grouped.

Level of Significance

All statistical evaluations in this study were carried out with a level of significance of 0.10. Considering the quality of data obtained in empirical studies of this nature, and the possible risks associated with the interpretations of results, it was felt that this level was fully warranted.
RESULTS AND DISCUSSION

Basically, the results of this study define empirical relationships between snowpack dynamics and readily available or easily obtained inventory variables common to the ponderosa pine type in Arizona. It is suggested, and will subsequently be developed, that the formulae and auxiliary analyses describing these relationships can be employed in estimating existing snowpack water yields and in predicting potentials for increasing water yields through forest-snow management.

Unfortunately, due to inherent differences in measurement and analysis objectives among study areas, unpredictable weather patterns, and logistic and scheduling difficulties, it was not possible to obtain or evaluate the full array of measurements necessary to characterize the specified snowpack conditions for each area and year in the study. On Campbell Blue, winter precipitation was apparently below normal the year of the study, and the peak accumulation of snow, which was also probably less than normal, melted rapidly. Consequently, detailed analyses of snowpack conditions associated with the spring run-off period was not possible. The two years of study on Beaver Creek, characterized by above normal winter precipitation, exhibited prolonged
melt periods, allowing evaluations to be made of snowpack conditions during the spring runoff period. However, because of the philosophy of sample plot location on Beaver Creek, within plot variations in timber overstory size class distributions limited inventory-prediction analyses with forest cover variables. Finally, as mentioned previously, snowpack measurements are made on a regular bi-monthly schedule on the snow courses utilized in the S.C.S. Cooperative Snow Surveys. Therefore, it is possible that specific events, such as actual peak accumulation or residual snowpack at the end of spring runoff, could have been missed.

**Inventory-Prediction Equations**

In general, the simple inventory-prediction relationships between snowpack dynamics and individual inventory variables developed in this study, when statistically significant, agreed with findings previously reported in other studies. However, in many instances, the mathematical model assumed was different.

Regardless of the expression of forest cover density the magnitude of snowpack water content measured increased as density decreased, which is consistent with studies made elsewhere (Anderson 1956, Baldwin 1957, Goodell 1965, Haupt 1951, Kittredge 1953, Lull and Rushmore 1960, Packer 1962, Urie 1966, Weitzman and Bay 1959,
Wilm and Dunford 1948). This general relationship was independent of slope percent, aspect, and elevation within the range sampled.

It was not possible to isolate statistical differences in snowpack water content under forest cover of similar density levels but different timber overstory size class compositions, possibly due to frequent intermingling of size classes and the selection of sample trees being based on point sampling techniques. With point sampling, which is basically sampling proportional to size (Beers and Miller 1964, Grosenbaugh 1958), small trees must be closer to sample points than larger trees to be tallied. Therefore, because they tend to be closer to sampling points, small trees could conceivably influence the snowpack at the point to at least the same degree as larger trees further away, obscuring size class differences. Whatever the cause, size class was omitted in considerations of inventory-prediction variables.

Greater snowpack water contents were generally measured on "cool" than "warm" sites, the former sites being indicative of low potential direct beam solar radiation, determined by slope and aspect, with the latter sites characterized by high values. This pattern of snowpack water content distribution, which represents the integration of accumulation and melt at a point in time, has been reported by others (Anderson and West 1965, Garn 1969, Garstka et al. 1958, Gary and Coltharp 1967, Haupt 1951, Packer 1962). There was no apparent
correlation between potential direct beam solar radiation and forest cover density variables.

The role of elevation as a snowpack inventory-prediction variable was inconclusive. Elevation was not analyzed on Campbell Blue. Relationships were inconsistent on Beaver Creek; but, when statistically significant, they did indicate greater snowpack water content at higher than lower elevations, as has been reported elsewhere (Anderson and Pagenhart 1957, Packer 1962). Relationships between snowpack water content and elevation were also inconsistent on the S.C.S. Cooperative Snow Survey Plots.

Soil, analyzed exclusively on Beaver Creek, was designated by soil management area, either Brolliar or Siesta-Sponseller, from existing soil maps (Williams and Anderson 1967). Analyses of variance showed no statistically significant differences between the soil management areas as related to snowpack water content at any time in the sample. Consequently, this soil parameter was disregarded in further considerations of potential inventory-prediction variables.

Analysis developed from the long-term data available from the S.C.S. Cooperative Snow Surveys indicated, as could be expected, greater snowpack water contents to be associated with greater precipitation inputs. A relationship developed between snowpack water content at assumed seasonal peak accumulation and total precipitation
inputs two months prior to this event was a linear function of high correlation, suitable for use in prediction. There appeared to be little relationship between precipitation and other inventory-prediction variables, at least within the range sampled.

Inventory-Prediction Equation Synthesis

After a cursory examination of the arrays of regression solutions relating snowpack conditions to forest cover density variables, it became evident that little statistical gain was achieved by allowing more than one algebraic or transcendental function describing forest cover to be included in inventory-prediction equations. Consequently, the most apparent statistically significant simple regression equation describing snowpack water content as a function of forest cover, determined by the standard error of estimate, the coefficient of determination, and the \( cp \) statistic, was selected as a base, to which potential direct beam solar radiation, elevation, when appropriate, and precipitation, when available, were added.

In many instances, the standard error of estimate and coefficient of determination were assumed to be statistically similar, with differences attributed to sampling. Therefore, the ultimate criterion was the \( cp \) statistic, simple regression equations with the smallest \( cp \) value being selected as a base. It was felt that, because simple
regression equations are of the same number of terms (variables), the \textit{cp} statistic could be used as a screener, equations with the smallest \textit{cp} value possessing small relative bias.

All possible combinations of forest cover density variables as related to snowpack water content will be presented. It is conceivable that models and combinations other than those selected as a base may be easier to interpret or apply in local situations.

As mentioned previously, all inventory-prediction equations will be keyed to a forest cover variable, as this will be the parameter subjected to land management re-direction evaluations designed to change potential snowpack water yields.

Limitations in Interpretations

Generally, operational water yield improvement programs currently being considered for implementation in Arizona to change potential snowpack water yields fall into two categories, the thinning or clearing of vegetation. Although there may be many intensities of thinning and arrangements of clearing, these two categories are the primary options available to upstream land management agencies for forest cover manipulation in the ponderosa pine type. The inventory-prediction equations developed and discussed in this study are valid only for the first category, the thinning of forest cover. It is entirely possible that similar relationships, using the same expressions of
dependent and independent variables, could be constructed for clearing operations, but no attempt to accomplish this end was made here.

As is common to any empirical study, application of relationships must be restricted to the range of conditions sampled. Thus, it is emphasized that the application and interpretation of the inventory-prediction equations developed here should not be extended beyond the limits of the independent variables sampled on the respective study areas (Tables 1, 2, and 3). Additionally, because only one year and two years of snowpack measurements were available on the Campbell Blue and Beaver Creek study areas, respectively, tentative interpretations must be made within this limitation. Data from the S.C.S. Cooperative Snow Surveys represent long study periods, however.

Solving the inventory-prediction equations for forest cover density values of zero, attempting to predict snowpack response to complete removal of all vegetation, is not valid. Forest cover variables considered in this study were developed from point sampling techniques employing a basal area factor of 25 as a base. With point sampling, if no trees are tallied at a sample point, all that can be said is that the point is not stocked to a basal area level corresponding to the basal area factor employed in the inventory (Roberts 1964), in this case, 25 square feet of basal area per acre. Even when considering the mean density associated with a cluster of sample points,
Table 1

Minimum, Mean, and Maximum of Independent Variables with a Continuous Distribution on the Campbell Blue Plots

<table>
<thead>
<tr>
<th>Variables</th>
<th>Unit of Measure</th>
<th>Min.</th>
<th>Mean</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest Cover:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basal area</td>
<td>Square feet basal area per acre</td>
<td>5</td>
<td>94</td>
<td>170</td>
</tr>
<tr>
<td>Sum of diameters</td>
<td>Inches per acre</td>
<td>57</td>
<td>1869</td>
<td>8176</td>
</tr>
<tr>
<td>Number of trees</td>
<td>Number per acre</td>
<td>6</td>
<td>340</td>
<td>1910</td>
</tr>
<tr>
<td>Bole area</td>
<td>Square feet bole area per acre</td>
<td>430</td>
<td>11132</td>
<td>24590</td>
</tr>
<tr>
<td>Volume</td>
<td>Cubic feet(^1) per acre</td>
<td>64</td>
<td>1616</td>
<td>4769</td>
</tr>
<tr>
<td>Number of trees in relation to height</td>
<td>(Height index)</td>
<td>0.40</td>
<td>1.22</td>
<td>3.19</td>
</tr>
<tr>
<td>Potential direct beam solar radiation(^2)</td>
<td>Langley's per solar day</td>
<td>655</td>
<td>716</td>
<td>863</td>
</tr>
<tr>
<td>Elevation</td>
<td>Feet</td>
<td>7990</td>
<td>8010</td>
<td>8090</td>
</tr>
</tbody>
</table>

\(^1\)Basis (Myers 1963b).

\(^2\)Index date: March 21 (Frank and Lee 1966).
Table 2

Minimum, Mean, and Maximum of Independent Variables with a Continuous Distribution on the Beaver Creek Plots

<table>
<thead>
<tr>
<th>Variables</th>
<th>Unit of Measure</th>
<th>Min.</th>
<th>Mean</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest Cover:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basal area</td>
<td>Square feet basal area per acre</td>
<td>0</td>
<td>103</td>
<td>220</td>
</tr>
<tr>
<td>Potential direct beam</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar radiation</td>
<td>Langleys per solar day</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1967-68(^1)</td>
<td></td>
<td>189</td>
<td>560</td>
<td>814</td>
</tr>
<tr>
<td>1968-69(^2)</td>
<td></td>
<td>370</td>
<td>696</td>
<td>881</td>
</tr>
<tr>
<td>Elevation</td>
<td>Feet</td>
<td>7325</td>
<td>7540</td>
<td>7720</td>
</tr>
</tbody>
</table>

\(^1\)Index date: February 7 (Frank and Lee 1966).

\(^2\)Index date: March 21 (Frank and Lee 1966).
Table 3

Minimum, Mean, and Maximum of Independent Variables with a Continuous Distribution on the S.C.S. Cooperative Snow Survey Plots

<table>
<thead>
<tr>
<th>Variables</th>
<th>Unit of Measure</th>
<th>Min.</th>
<th>Mean</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest Cover:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basal area</td>
<td>Square feet basal area per acre</td>
<td>23</td>
<td>58</td>
<td>134</td>
</tr>
<tr>
<td>Potential direct beam</td>
<td>Langleys per solar</td>
<td>548</td>
<td>658</td>
<td>706</td>
</tr>
<tr>
<td>Solar radiation¹</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elevation</td>
<td>Feet</td>
<td>6000</td>
<td>7280</td>
<td>8100</td>
</tr>
</tbody>
</table>

¹ Index date: March 7 (Frank and Lee 1966).
density levels of zero can not be implied. Similar arguments can be developed for the other expressions of forest density. Also, aside from the mensurational aspects, sites characterized by low density levels approaching zero located in the middle of a forest stand do not necessarily simulate extensive clearings as these respective sites may affect snowpack distribution patterns.

Finally, all studies must be restricted by the specific procedures used in satisfying the objectives. Here, the interpretation and application of results must be made within the framework of the sampling designs employed, snowpack measurement schedules, point sampling theories and techniques, and analytic methodologies and assumptions.

Winter Accumulation-Melt Period

A period representing late winter accumulation-melt conditions was selected for snowpack measurement to index the combined influence of winter precipitation inputs and losses to interception vaporization or temporary interception retention. The net result of this integration of inputs and losses over time is a possible redistribution of residual precipitation, as measured by snowpack water content. This measurement period, considered representative of the winter build-up of a snowpack, was important as it may lend insight into management
procedures necessary to increase subsequent peak accumulation, prior to spring runoff.

The actual time of snowpack measurement for characterization of winter accumulation-melt was an arbitrarily selected date indicative of a 7- to 10-day precipitation-free period following a large winter storm. Several measurements were made on both Campbell Blue and Beaver Creek before data meeting the above criterion were obtained. It was not possible to consistently define these conditions on the S.C.S. Cooperative Snow Survey Plots in the sample because of the rigid measurement schedule imposed; consequently, winter accumulation-melt conditions were not analyzed on these snow courses.

Basal Area. Relationships between snowpack water content and basal area were not statistically significant on the Beaver Creek study area for any winter accumulation-melt period measurement made in the two years of study. Therefore, inventory-prediction equations were developed on Campbell Blue.

Little statistical differences occurred between the linear and logarithmic models describing snowpack water content as a function of basal area (Table 4). However, using the cp statistic criterion, the logarithmic model was selected as a base, to which potential direct beam solar radiation was combined in a multiple regression. The resulting inventory-prediction equation follows:
Table 4

Inventory-Prediction Equations Describing Snowpack Water Content during Winter Accumulation-Melt as a Function of Basal Area—Campbell Blue

<table>
<thead>
<tr>
<th>Equation Number</th>
<th>Equations</th>
<th>( s_y.x )</th>
<th>( r^2 )</th>
<th>( cp )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple regressions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>( Y = 3.07 - 0.0166 , BA )</td>
<td>0.76</td>
<td>0.41</td>
<td>7.19</td>
</tr>
<tr>
<td>2</td>
<td>( Y = 1.40 + 11.8/BA )</td>
<td>0.86</td>
<td>0.25</td>
<td>19.06</td>
</tr>
<tr>
<td>3</td>
<td>( Y = 2.33 - 0.773 \times 10^{-4} , BA^2 )</td>
<td>0.85</td>
<td>0.25</td>
<td>17.45</td>
</tr>
<tr>
<td>4</td>
<td>( Y = 5.33 - 0.859 , \ln BA )</td>
<td>0.74</td>
<td>0.44</td>
<td>5.25</td>
</tr>
<tr>
<td>Multiple regressions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>( Y = 3.92 - 0.420 , BA + 0.152 ) (10^{-3})BA^2</td>
<td>0.71</td>
<td>0.51</td>
<td>2.30</td>
</tr>
<tr>
<td>6</td>
<td>( Y = 12.4 - 25.2 , BA + 0.635 ) (10^{-4})BA^2 - 2.52 , \ln BA</td>
<td>0.71</td>
<td>0.52</td>
<td>3.03</td>
</tr>
<tr>
<td>7</td>
<td>( Y = 9.94 - 0.0189 , BA - 18.8/BA + 0.116 \times 10^{-3} ) BA^2 - 1.70 , \ln BA</td>
<td>0.71</td>
<td>0.53</td>
<td>5.00</td>
</tr>
<tr>
<td></td>
<td>( a = 0.10, , n = 40 )</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Dependent variable -- \( Y \) is snowpack water content (WE) representing the winter accumulation-melt period (February 22, 1969), in inches.

Independent variable -- \( BA \) is basal area, in square feet per acre. \( \ln BA \) is logarithm of basal area, in square feet per acre.

\(^1\) Mean snowpack water content (WE) of 1.70 inches.
\[ Y = 11.1 - 0.750 \ln BA - 0.0110 R_{ps} \]  

where \( Y \) is snowpack water content (WE) representing the winter accumulation-melt period (February 22, 1969), in inches.

\( \ln BA \) is logarithm of basal area, in square feet per acre.

\( R_{ps} \) is potential direct beam solar radiation received during solar day on index date (February 20), in Langley's (Frank and Lee 1966).

The associated, descriptive statistics are:

\[ S_{y.x} = 0.60 \text{ inches} \]

where \( S_{y.x} \) is the standard error of estimate with mean snowpack water content (WE) of 1.70 inches.

\[ r^2 = 0.65 \]

**Sum of Diameters.** As with basal area, relationships on Beaver Creek were not statistically significant, limiting analyses of the sum of diameters as a snowpack inventory-prediction variable to Campbell Blue.

Based on examination of the array of inventory-prediction equations describing snowpack water content as a function of the
sum of diameters (Table 5), this expression of forest cover does not appear as statistically significant as basal area. Although somewhat similar to basal area in mensurational development, the sum of diameters gives more relative weight to the smaller trees. Apparently the reverse is more important in considering snowpack dynamics, with large trees affecting distribution patterns to a greater extent than small trees. This supposition can only be implied because direct measurements of the relative influences of trees size on snowpack dynamics were not made. It has previously been stated that it was not possible to isolate differences attributed to timber overstory size class.

Little additional knowledge was gained by combining potential direct beam solar radiation with a sum of diameters base, which, as with basal area, was assumed to be a logarithmic model.

**Number of Trees.** What would seem a logical measure of forest cover density, and a possible index of the different processes influencing snowpack dynamics, number of trees per unit area, was not statistically significant on Beaver Creek, and was but weakly correlated with snowpack water content on Campbell Blue. No simple regression was statistically significant on Campbell Blue. Only by combining more than one algebraic or transcendental function describing number of trees into multiple regressions could significance be realized (Table 6). Inventory-prediction equations including potential direct beam solar radiation were not developed because of the
Table 5

Inventory-Prediction Equations Describing Snowpack Water Content during Winter Accumulation-Melt during Function of the Sum of Diameters--Campbell Blue

<table>
<thead>
<tr>
<th>Equation Number</th>
<th>Equations</th>
<th>$S_{y.x}$</th>
<th>$r^2$</th>
<th>cp</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$Y = 2.12 - 0.244 \times 10^{-3} SD$</td>
<td>0.91</td>
<td>0.15</td>
<td>13.57</td>
</tr>
<tr>
<td>2</td>
<td>$Y = 1.60 + 26.8/SD$</td>
<td>0.96</td>
<td>0.07</td>
<td>18.46</td>
</tr>
<tr>
<td>3</td>
<td>$Y = 5.08 - 0.475 \ln SD$</td>
<td>0.85</td>
<td>0.27</td>
<td>6.48</td>
</tr>
<tr>
<td></td>
<td><strong>Multiple regressions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>$Y = 7.23 - 41.0/SD - 0.761 \ln SD$</td>
<td>0.82</td>
<td>0.33</td>
<td>4.96</td>
</tr>
<tr>
<td>5</td>
<td>$Y = 11.5 + 0.336 \times 10^{-3}SD - 85.6 SD - 1.43 \ln SD$</td>
<td>0.79</td>
<td>0.39</td>
<td>3.34</td>
</tr>
<tr>
<td>6</td>
<td>$Y = 13.0 + 0.663 \times 10^{-3}SD - 100/SD - 0.306 \times 10^{-7}$</td>
<td>0.80</td>
<td>0.40</td>
<td>5.00</td>
</tr>
</tbody>
</table>

$\text{SD}^2 - 1.70 \ln SD$

$a = 0.10, n = 40$

Dependent variable - (Y) is snowpack water content (WE) representing the winter accumulation-melt period (February 22, 1969), in inches.

Independent variable - (SD) is the sum of diameters, in inches per acre. (ln SD) is logarithm of the sum of diameters, in inches per acre.

1 Mean snowpack water content (WE) of 1.70 inches.
Table 6

Inventory-Prediction Equations Describing Snowpack Water Content during Winter Accumulation-Melt as a Function of Number of Trees--Campbell Blue

<table>
<thead>
<tr>
<th>Equation Number</th>
<th>Equations</th>
<th>$S_{y.x}$</th>
<th>$r^2$</th>
<th>$cp$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple regressions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>$Y = 3.48 + 0.571(10^{-6})$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$NO^2 - 0.376 \ln NO$</td>
<td>0.94</td>
<td>0.12</td>
<td>1.19</td>
</tr>
<tr>
<td>Multiple regressions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>$Y = 3.98 - 3.97/NO +$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$0.643(10^{-6}) - 0.469$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\ln NO$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$NO = 3.14/NO$</td>
<td>0.95</td>
<td>0.12</td>
<td>3.00</td>
</tr>
<tr>
<td>3</td>
<td>$Y = 3.76 - 0.264(10^{-3})$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$NO = 3.14/NO$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$+ 0.742(10^{-6})NO^2 -$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$0.415 \ln NO$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$a = 0.10, n = 40$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Dependent variable - $(Y)$ is snowpack water content (WE) representing the winter accumulation-melt period (February 22, 1969), in inches.

Independent variable - $(NO)$ is number of trees, in number per acre. $(\ln NO)$ is logarithm of number of trees, in number per acre.

1 Mean snowpack water content (WE) of 1.70 inches.
low degree of correlation between snowpack water content and number of trees.

**Bole Area.** Inventory-prediction equations describing snowpack water content as a function of bole area were not statistically significant on Beaver Creek, possibly due to a confounding affect caused by the intermingling of Gambel oak on many of the sample plots.

Although bole area possibly reflects different processes influencing snowpack dynamics than basal area, the statistical form and relative significance of both expressions were similar on Campbell Blue (Tables 4 and 7). The empirical nature of this study precluded the evaluation of these two expressions of forest density separately. Therefore, the significance of bole area vis-a-vis basal area in affecting snowpack distribution patterns can not be determined individually, but, based on statistical similarities, they conceivably have similar effects.

Again, as with basal area, using the $c_p$ statistic, the logarithmic model was selected as a forest cover base (Table 7), to which potential direct beam solar radiation was combined in a multiple regression. The resulting inventory-prediction equation follows:

$$Y = 13.3 - 0.600 \ln BO - 0.0109 R_{ps}$$

(2)

where $Y$ is snowpack water content (WE) representing the winter accumulation-melt period (February 22, 1969), in inches.
Table 7

Inventory-Prediction Equations Describing Snowpack Water Content during Winter Accumulation-Melt as a Function of Bole Area--Campbell Blue

<table>
<thead>
<tr>
<th>Equation Number</th>
<th>Equations</th>
<th>$S_{y.x}$</th>
<th>$r^2$</th>
<th>cp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple regressions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>$Y = 2.88 - 0.109(10^{-3})BO$</td>
<td>0.79</td>
<td>0.37</td>
<td>2.77</td>
</tr>
<tr>
<td>2</td>
<td>$Y = 1.46 + 973/BO$</td>
<td>0.87</td>
<td>0.22</td>
<td>12.03</td>
</tr>
<tr>
<td>3</td>
<td>$Y = 2.23 - 0.368(10^{-8})BO^2$</td>
<td>0.85</td>
<td>0.26</td>
<td>9.65</td>
</tr>
<tr>
<td>4</td>
<td>$Y = 8.13 - 0.710\ln BO$</td>
<td>0.78</td>
<td>0.38</td>
<td>2.27</td>
</tr>
<tr>
<td>Multiple regressions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>$Y = 3.46 - 0.235(10^{-3})BO + 0.536(10^{-8})BO^2$</td>
<td>0.76</td>
<td>0.43</td>
<td>1.55</td>
</tr>
<tr>
<td>6</td>
<td>$Y = 3.16 - 0.251(10^{-3})BO + 0.576(10^{-8}) + 0.0450\ln BO$</td>
<td>0.77</td>
<td>0.43</td>
<td>3.54</td>
</tr>
<tr>
<td>7</td>
<td>$Y = 12.1 - 0.580(10^{-3})BO + 1660/BO + 0.123(10^{-7})BO + 1.98 \ln BO$</td>
<td>0.77</td>
<td>0.43</td>
<td>5.00</td>
</tr>
</tbody>
</table>

Dependent variable - $(Y)$ is snowpack water content (WE) representing the winter accumulation-melt period (February 22, 1969), in inches.

Independent variables - $(BO)$ is bole area, in square feet per acre. $(\ln BO)$ is logarithm of bole area, in square feet per acre.

$1$ Mean snowpack water content (WE) of 1.70 inches.
lnBO is logarithm of bole area, in square feet per acre.

$R_{ps}$ is potential direct beam solar radiation received during solar day on index date (February 20), in Langley (Frank and Lee 1966).

The associated, descriptive statistics are:

$$S_{y.x} = 0.65 \text{ inches}$$

where $S_{y.x}$ is the standard error of estimate with mean snowpack water content (WE) of 1.70 inches.

$$r^2 = 0.58$$

**Volume.** Relationships between snowpack water content and volume of the forest cover, necessary to analyze trade-offs between forest-based products, were developed only on Campbell Blue. After examining the array of inventory-prediction equations (Table 8), the logarithmic model was again selected as a base, to which potential direct beam solar radiation was added. The resulting equation follows:

$$Y = 12.0 - 0.579 \ln V - 0.0108 R_{ps} \quad (3)$$

where $Y$ is snowpack water content (WE) representing the winter accumulation-melt period (February 22, 1969), in inches.
Table 8

Inventory-Prediction Equations Describing Snowpack Water Content during Winter Accumulation-Melt as a Function of Volume--Campbell Blue

<table>
<thead>
<tr>
<th>Equation Number</th>
<th>Equations</th>
<th>$s_{y.x}$</th>
<th>$r^2$</th>
<th>$cp$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Simple regressions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>$Y = 2.57 - 0.567 \times 10^{-3}V$</td>
<td>0.80</td>
<td>0.35</td>
<td>11.39</td>
</tr>
<tr>
<td>2</td>
<td>$Y = 1.38 + 165/V$</td>
<td>0.84</td>
<td>0.28</td>
<td>16.40</td>
</tr>
<tr>
<td>3</td>
<td>$Y = 1.99 - 0.901 \times 10^{-7}V^2$</td>
<td>0.90</td>
<td>0.18</td>
<td>23.47</td>
</tr>
<tr>
<td>4</td>
<td>$Y = 6.52 - 0.686 \ln V$</td>
<td>0.73</td>
<td>0.46</td>
<td>3.07</td>
</tr>
<tr>
<td></td>
<td>Multiple regressions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>$Y = 8.69 - 0.970/V - 0.970 \ln V$</td>
<td>0.74</td>
<td>0.49</td>
<td>3.49</td>
</tr>
<tr>
<td>6</td>
<td>$Y = 12.6 + 0.361 \times 10^{-3}V - 203/V - 1.58 \ln V$</td>
<td>0.72</td>
<td>0.50</td>
<td>4.20</td>
</tr>
<tr>
<td>7</td>
<td>$Y = 20.5 + 0.00206V - 367/V - 0.210 \times 10^{-6}V^2 - 2.93 \ln V$</td>
<td>0.72</td>
<td>0.52</td>
<td>5.00</td>
</tr>
</tbody>
</table>

$a = 0.10, n = 40$

Dependent variable - ($Y$) is snowpack water content (WE) representing the winter accumulation-melt period (February 22, 1969), in inches.

Independent variables - ($V$) is volume, in cubic feet (Myers 1963b) per acre.

($\ln V$) is logarithm of volume, in cubic feet (Myers 1963b) per acre.

\(^1\)Mean snowpack water content (WE) of 1.70 inches.
\( \ln V \) is the logarithm of volume, in cubic feet (Myers 1963b) per acre.

\( R_{ps} \) is potential direct beam solar radiation received during solar day on index date (February 20), in Langley's (Frank and Lee 1966).

The associated, descriptive statistics are:

\[
S_{y.x} = 0.59 \text{ inches}
\]

where \( S_{y.x} \) is the standard error of estimate with mean snowpack water content (WE) of 1.70 inches.

\[
r^2 = 0.66
\]

**Number of Trees in Relation to Height.** Relationships between snowpack content and height-index values were not statistically significant on Beaver Creek. Thus, inventory-prediction equations were developed only from data obtained on a subsample of uniformly stocked, even-aged forest cover sample plots located on the Campbell Blue study area.

As stated previously, the linkage between processes influencing snowpack dynamics and a height-based measure of forest density, independent of tree diameter, is not clearly understood. However, based on the high correlation \((r = -0.783, n = 16)\) between snowpack water content and height-index (Table 9, the hyperbolic model), height-index is a sensitive measure of biomass affecting the processes
Table 9

Inventory-Prediction Equations Describing Snowpack Water Content during Winter Accumulation-Melt as a Function of Height-Index—Campbell Blue

<table>
<thead>
<tr>
<th>Equation Number</th>
<th>Equations</th>
<th>$S_{Y,x}$</th>
<th>$r^2$</th>
<th>cp</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Simple regressions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>$Y = 2.04 - 0.616HI$</td>
<td>0.69</td>
<td>0.28</td>
<td>12.66</td>
</tr>
<tr>
<td>3</td>
<td>$Y = 0.105 - 1.13/HI$</td>
<td>0.51</td>
<td>0.61</td>
<td>1.31</td>
</tr>
<tr>
<td>4</td>
<td>$Y = 1.53 - 0.127 HI^2$</td>
<td>0.75</td>
<td>0.15</td>
<td>17.06</td>
</tr>
<tr>
<td>5</td>
<td>Multiple regressions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>$Y = -0.955 + 2.07/HI + 1.04 lnHI$</td>
<td>0.49</td>
<td>0.66</td>
<td>1.80</td>
</tr>
<tr>
<td>7</td>
<td>$Y = -1.22 - 1.22HI + 3.54/HI + 4.04 lnHI$</td>
<td>0.50</td>
<td>0.68</td>
<td>3.14</td>
</tr>
<tr>
<td></td>
<td>$+ 6.14/HI + 0.889 HI^2 + 12.3 lnHI$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$\alpha = 0.10$, $n = 16$

Dependent variable - (Y) is snowpack water content (WE) representing the winter accumulation-melt period (February 22, 1969), in inches.

Independent variables - (HI) is height-index (Larson and Minor 1968) (ln HI) is logarithm of height-index (Larson and Minor 1968)

$^1$Mean snowpack water content (WE) of 1.35 inches.
influencing snowpack dynamics. Additional mensurational exploration will be required to attain an understanding of why this specific measure of biomass yields statistical gains over the other expressions of forest density.

The hyperbolic model describing snowpack water content as a function of height-index was selected as a forest cover base (Table 9), to which potential direct beam solar radiation was combined in a multiple regression. The resulting inventory-prediction equation follows:

\[ Y = 5.49 + 0.687/HI - 0.00851 R_{ps} \]  \hspace{1cm} (4)

where \( Y \) is snowpack water content (WE) representing the winter accumulation-melt period (February 22, 1969), in inches.

\( HI \) is height-index (Larson and Minor 1968).

\( R_{ps} \) is potential direct beam solar radiation received during solar day on index date (February 20), in Langley's (Frank and Lee 1966).

The associated, descriptive statistics are:

\[ s_{y.x} = 0.28 \text{ inches} \]

where \( s_{y.x} \) is the standard error of estimate with mean snowpack water content (WE) of 1.35 inches.

\[ r^2 = 0.69 \]
Peak Accumulation, Prior to Spring Runoff

The magnitude of snowpack water content at the time of late winter peak accumulation, just prior to the start of spring runoff, is a key management criterion because, theoretically, this quantity represents the best estimate of the potential for recoverable water yield from snow. As with the winter accumulation-melt period, snowpack measurement at this time characterizes the integration of precipitation inputs, losses, and re-distribution over time. In addition to its significance in attempting to predict subsequent water yields, quantification of snowpack distribution patterns at this time is important as it may define forest-snow interactions necessary to prescribe effective land management systems designed to change potential snowpack water yields.

The time of peak snowpack accumulation, prior to spring runoff, can not be determined until after the fact. Therefore, several measurements were made on Campbell Blue and Beaver Creek before acceptable data were obtained. Assumed peak snowpack accumulations on the S.C.S. Cooperative Snow Survey snow courses were defined as described above.

**Basal Area.** Inventory-prediction equations describing peak accumulation snowpack water content as a function of basal area on the Campbell Blue study area (Table 10) showed little statistical
Table 10

Inventory-Prediction Equations Describing Snowpack Water Content at Peak Accumulation, prior to Spring Runoff, as a Function of Basal Area--Campbell Blue

<table>
<thead>
<tr>
<th>Equation Number</th>
<th>Equations</th>
<th>$S_{y·x}$</th>
<th>$r^2$</th>
<th>cp</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$Y = 3.53 - 0.0194 BA$</td>
<td>1.02</td>
<td>0.35</td>
<td>6.91</td>
</tr>
<tr>
<td>2</td>
<td>$Y = 1.55 + 15.0/BA$</td>
<td>1.09</td>
<td>0.25</td>
<td>13.21</td>
</tr>
<tr>
<td>3</td>
<td>$Y = 2.64 - 0.874(10^{-4})BA^2$</td>
<td>1.12</td>
<td>0.22</td>
<td>15.59</td>
</tr>
<tr>
<td>4</td>
<td>$Y = 6.35 - 1.05 \ln BA$</td>
<td>0.98</td>
<td>0.40</td>
<td>3.32</td>
</tr>
<tr>
<td>5</td>
<td>$Y = 4.71 - 0.0546 BA + 0.211(10^{-3})BA^2$</td>
<td>0.94</td>
<td>0.46</td>
<td>1.64</td>
</tr>
<tr>
<td>6</td>
<td>$Y = 14.7 - 28.9/BA + 0.858(10^{-4})BA^2 - 3.03 \ln BA$</td>
<td>0.95</td>
<td>0.47</td>
<td>3.05</td>
</tr>
<tr>
<td>7</td>
<td>$Y = 10.5 - 0.0318 BA - 18.2/BA + 0.174(10^{-3})BA^2 - 1.65 \ln BA$</td>
<td>0.96</td>
<td>0.47</td>
<td>5.00</td>
</tr>
</tbody>
</table>

$a = 0.10$, $n = 40$

Dependent variable - $(Y)$ is snowpack water content $(WE)$ representing peak accumulation, prior to spring runoff (March 15, 1969), in inches.

Independent variables - $(BA)$ is basal area, in square feet per acre. $(\ln BA)$ is logarithm of basal area, in square feet per acre.

Mean snowpack water content $(WE)$ of 2.00 inches.
difference, except those attributed to a greater water content, as opposed to equations developed for the winter accumulation-melt period. Consequently, it was thought possible that basal area, as a inventory-prediction variable, had similar significance in terms of snowpack distribution patterns throughout the winter accumulation period.

Again, the logarithmic model was selected as a forest cover base (Table 10), to which potential direct beam solar radiation was added. The resulting equation follows:

\[ Y = 16.5 - 0.806 \ln BA - 0.0157 \, R_{ps} \quad (5) \]

where \( Y \) is snowpack water content (WE) representing peak accumulation, prior to spring runoff (March 15, 1969), in inches.

\( \ln BA \) is logarithm of basal area, in square feet per acre.

\( R_{ps} \) is potential direct beam solar radiation received during solar day on index date (March 21), in Langleys (Frank and Lee 1966).

The associated, descriptive statistics are:

\[ S_{y \cdot x} = 0.80 \text{ inches} \]

where \( S_{y \cdot x} \) is the standard error of estimate with mean snowpack water content (WE) of 2.00 inches.

\[ r^2 = 0.61 \]
Snowpack water content at peak accumulation was not correlated with basal area in simple regression analyses in the two years of study on Beaver Creek, possibly due to the within sample plot variations in timber overstory size class distributions. It was assumed, therefore, that multiple regressions combining basal area, potential direct beam solar radiation, and elevation would not be statistically valid, because a stated restriction of the regression combinations was that a forest cover variable must appear.

Snowpack water content was statistically correlated with potential direct beam solar radiation ($r = -0.526$, $n = 75$ on February 10, 1968, and $r = -0.254$, $n = 75$ on March 15, 1969), but not with elevation.

In addition to the within plot variations in timber overstory, other possible reasons for the lack of correlation between snowpack water content and basal area on Beaver Creek could be ascribed to the geographic location of the sample plots with respect to surrounding topography, or to the fact that precipitation inputs in the two years of study were above normal, which perhaps caused less total variations in peak accumulation snowpack distributions. The majority of the sample plots on Beaver Creek were located on or within one-half mile of a predominant topographic feature (Lake Mountain), which, because of its position relative to winter storm movements, may have influenced
snowpack distributions. This, coupled with the above normal precipitation inputs, particularly the record snowfall of 1967-68 (Enz 1968), could have conceivably "masked" effects that forest cover may have on processes influencing snowpack dynamics.

Data available from the S.C.S. Cooperative Snow Surveys were used in attempting construction of an inventory-prediction equation describing peak accumulation snowpack water content as a function of basal area, precipitation inputs, potential direct beam solar radiation, and elevation. Such an equation could be used to predict mean snowpack water content on a basin, given knowledge of the independent variables. Also, with this equation, it may be possible to evaluate the relative effect of the different inventory-prediction variables on snowpack dynamics over time.

Assuming statistical independence among sample plots (snow courses) and all potential variables, including precipitation inputs for different years, simple regressions were developed to analyze the contributions of the individual inventory-prediction variables. Analyses included within and between year evaluations of basal area, potential direct beam solar radiation, and elevation, as these variables may relate to snowpack dynamics for and among given precipitation inputs. Also, simple regressions describing snowpack water content as functions of various indices of precipitation input were
developed, attempting to identify a useful measure of precipitation as relating to snowpack dynamics.

Simple regressions involving basal area, potential direct beam solar radiation, or elevation were statistically non-significant. As the snow courses comprising this sample were not necessarily located to sample these variables, and because of the relatively small number of data points, these results can not be considered conclusive over the entire range of conditions in the ponderosa pine type.

Total precipitation inputs for two months prior to peak accumulation, determined from precipitation measurements obtained at the snow courses or from nearby U.S. Weather Bureau stations, was highly correlated with snowpack water content. Considering each event, i.e., peak accumulation at a snow course for a given year, to be statistically independent, over 75 percent of the variation in peak accumulation snowpack water content was associated with this index of precipitation. Because of this high correlation, and because of the potential value in predicting basin means, an inventory-prediction equation was developed, making an exception to the constraint of a forest cover variable appearing in every regression. This equation, based on 134 events occurring at 16 snow courses, follows:

\[ Y = 0.36 + 0.760 P_i \] (6)
where $Y$ is snowpack water content (WE) representing peak accumulation, prior to spring runoff, in inches.

$P_i$ is total precipitation inputs two months preceding peak accumulation, in inches.

The associated, descriptive statistics are:

$$S_{\bar{y},x} = 1.70 \text{ inches}$$

where $S_{\bar{y},x}$ is the standard error of estimate with mean snowpack water content (WE) of 5.30 inches.

$$r^2 = 0.76$$

**Point Density.** On both Campbell Blue and Beaver Creek, snowpack water content at peak accumulation was statistically correlated with basal area computed by the angle-summation method, but not to a degree comparable with correlations developed from sample plot angle-count means. Apparently, the variability associated with point measurements of snowpack water content can not be overcome by this measure of basal area bearing upon an individual point.

There was no statistical differences among the simple correlation coefficients describing the association between snowpack water content and basal area determined by 1-, 2-, 3-, 4-, and 5-tree plots on Campbell Blue. Differences did occur on Beaver Creek (Table 11)
Table 11

Correlation Coefficients Describing Association between Snowpack Water Content at Peak Accumulation, Prior to Spring Runoff, and Basal Area Determined by 1-, 2-, 3-, 4-, and 5-Tree Plots

<table>
<thead>
<tr>
<th>Snowpack variable</th>
<th>Campbell Blue</th>
<th>1-tree</th>
<th>2-tree</th>
<th>3-tree</th>
<th>4-tree</th>
<th>5-tree</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.298</td>
<td>0.276</td>
<td>0.266</td>
<td>0.242</td>
<td>0.238</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.298</td>
<td>0.276</td>
<td>0.266</td>
<td>0.242</td>
<td>0.238</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Snowpack variable</th>
<th>Beaver Creek</th>
<th>1-tree</th>
<th>2-tree</th>
<th>3-tree</th>
<th>4-tree</th>
<th>5-tree</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>n.s.</td>
<td>2.320</td>
<td>0.413</td>
<td>0.460</td>
<td>0.529</td>
</tr>
<tr>
<td></td>
<td></td>
<td>n.s.</td>
<td>0.371</td>
<td>0.475</td>
<td>0.531</td>
<td>0.609</td>
</tr>
</tbody>
</table>

Any two correlation coefficients not underscored by the same line are statistically different.
Any two correlation coefficients underscored by the same line are not statistically different.
however, due primarily to correlation coefficients characterizing the 1-tree plots not being significant. Further testing is required before defining the advantages, if any, of the different tree-plot bases.

**Sum of Diameters.** Relationships between snowpack water content at peak accumulation and the sum of diameters, developed only on Campbell Blue (Table 12), were statistically similar to relationships developed for the winter accumulation-melt period. Again, as with basal area, this could indicate that the sum of diameters, as an empirical variable, had similar significance throughout the accumulation period. Inventory-prediction equations including potential direct beam solar radiation were not developed.

**Number of Trees.** Inventory-prediction equations describing snowpack water content at peak accumulation as a function of number of trees were not statistically significant on Beaver Creek, and, as was the case for the winter accumulation-melt period, were of little significance on Campbell Blue. Only by combining more than one transformed function describing number of trees into multiple regressions could statistical significance be attained (Table 13). Equations including potential direct beam solar radiation were not developed.

**Bole Area.** Relationships between snowpack water content and bole area, developed to characterize peak accumulation on Campbell Blue (Table 14), were, as with simple relationships including other
### Table 12

Inventory-Prediction Equations Describing Snowpack Water含量 at Peak Accumulation, Prior to Spring Runoff, as a Function of the Sum of Diameters—Campbell Blue

<table>
<thead>
<tr>
<th>Equation Number</th>
<th>Equations</th>
<th>$S_{y\cdot x}$</th>
<th>$r^2$</th>
<th>cp</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Single regressions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>$Y = 2.45 - 0.295\left(10^{-3}\right)SD$</td>
<td>1.17</td>
<td>0.14</td>
<td>2.01</td>
</tr>
<tr>
<td>2</td>
<td>$Y = 1.80 + \frac{38.9}{SD}$</td>
<td>1.21</td>
<td>0.09</td>
<td>14.71</td>
</tr>
<tr>
<td>3</td>
<td>$Y = 6.26 - 0.609\ln SD$</td>
<td>1.08</td>
<td>0.28</td>
<td>4.14</td>
</tr>
<tr>
<td><strong>Multiple regressions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>$Y = 8.39 - 40.6/SD - \frac{0.891}{\ln SD}$</td>
<td>1.06</td>
<td>0.31</td>
<td>4.23</td>
</tr>
<tr>
<td>5</td>
<td>$Y = 13.6 + 0.408SD - 94.7/SD - 1.70\ln SD$</td>
<td>1.03</td>
<td>0.37</td>
<td>3.09</td>
</tr>
<tr>
<td>6</td>
<td>$Y = 14.6 + 0.632\left(10^{-3}\right)SD - \frac{105}{SD} - \frac{0.210}{\left(10^{-7}\right)}SD^2 - 1.89\ln SD$</td>
<td>1.04</td>
<td>0.37</td>
<td>5.00</td>
</tr>
</tbody>
</table>

$a = 0.10, n = 40$

Dependent variable — \((Y)\) is snowpack water content \((WE)\) representing peak accumulation, prior to spring runoff (March 15, 1969), in inches.

Independent variables — \((SD)\) is the sum of diameters, in inches per acre.

\((\ln SD)\) is logarithm of the sum of diameters, in inches per acre.

\(^1\)Mean snowpack water content \((WE)\) of 2.00 inches.
Table 13

Inventory-Prediction Equations Describing Snowpack Water Content at Peak Accumulation, Prior to Spring Runoff, as a Function of Number of Trees--Campbell Blue

<table>
<thead>
<tr>
<th>Equation Number</th>
<th>Equations</th>
<th>$S_{y.x}$</th>
<th>$r^2$</th>
<th>cp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single regressions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>$Y = 4.54 + 0.732 \times (10^{-6})N0^2 - 0.543 \ln N0$</td>
<td>1.19</td>
<td>0.14</td>
<td>1.08</td>
</tr>
<tr>
<td>Multiple regressions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>$Y = 4.94 - 3.18/N0 + 0.790 \times (10^{-6})N0^2 - 0.617 \ln N0$</td>
<td>1.20</td>
<td>0.14</td>
<td>3.00</td>
</tr>
<tr>
<td>3</td>
<td>$Y = 4.58 - 0.419(10^{-3})N0 - 1.86/N0 + 0.946 \times (10^{-6})N0^2 - 0.533 \ln N0$</td>
<td>1.22</td>
<td>0.14</td>
<td>5.00</td>
</tr>
</tbody>
</table>

$a = 0.10, n = 40$

Dependent variable - (Y) is snowpack water content (WE) representing peak accumulation, prior to spring runoff (March 15, 1969), in inches.

Independent variables - (N0) is number of trees, in number per acre. (lnN0) is logarithm of number of trees, in number per acre.

1Mean snowpack water content (WE) of 2.00 inches.
Table 14

Inventory-Prediction Equations Describing Snowpack Water Content at Peak Accumulation, Prior to Spring Runoff, as a Function of Bole Area--Campbell Blue

<table>
<thead>
<tr>
<th>Equation Number</th>
<th>Equations</th>
<th>$S_{Y\cdot x}$</th>
<th>$r^2$</th>
<th>$cp$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$Y = 3.36 - 0.132(10^{-3})B_0$</td>
<td>1.03</td>
<td>0.34</td>
<td>2.36</td>
</tr>
<tr>
<td>2</td>
<td>$Y = 1.63 + 1250/B_0$</td>
<td>1.11</td>
<td>0.23</td>
<td>8.80</td>
</tr>
<tr>
<td>3</td>
<td>$Y = 2.57 - 0.441(10^{-8})B_0^2$</td>
<td>1.11</td>
<td>0.23</td>
<td>8.49</td>
</tr>
<tr>
<td>4</td>
<td>$Y = 9.97 - 0.887 \ln B_0$</td>
<td>1.00</td>
<td>0.37</td>
<td>0.71</td>
</tr>
</tbody>
</table>

**Simple regressions**

<table>
<thead>
<tr>
<th>Equation Number</th>
<th>Equations</th>
<th>$S_{Y\cdot x}$</th>
<th>$r^2$</th>
<th>$cp$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>$Y = 4.13 - 0.297(10^{-3})B_0$</td>
<td>1.00</td>
<td>0.39</td>
<td>1.19</td>
</tr>
<tr>
<td></td>
<td>$+ 0.699(10^{-8})B_0^2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>$Y = 3.90 - 0.266(10^{-3})B_0$</td>
<td>1.01</td>
<td>0.39</td>
<td>3.11</td>
</tr>
<tr>
<td></td>
<td>$+ 1.54/B_0 + 0.597 (10^{-8})B_0^2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>$Y = -5.57 - 0.478(10^{-3})$</td>
<td>1.02</td>
<td>0.40</td>
<td>5.00</td>
</tr>
<tr>
<td></td>
<td>$+ 1150/B_0 + 0.103$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$(10^{-7})B_0^2 + 1.20 \ln B_0$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$\alpha = 0.10, n = 40$

Dependent variable - ($Y$) is snowpack water content (WE) representing peak accumulation, prior to spring runoff (March 15, 1969), in inches.

Independent variables - ($B_0$) is bole area, in square feet per acre. ($\ln B_0$) is logarithm of bole area, in square feet per acre.

$^1$Mean snowpack water content (WE) of 2.00 inches.
other forest cover variables, comparable to those synthesized for the
winter accumulation-melt period. Using the cp statistic criterion, the
logarithmic model was selected as a base, to which potential direct
beam solar radiation was combined in a multiple regression. The re-
sulting inventory-prediction equation follows:

\[ Y = 19.2 - 0.658 \ln B_0 - 0.0158 R_{ps} \]  

where \( Y \) is snowpack water content (WE) representing
peak accumulation, prior to spring runoff
(March 15, 1969), in inches.

\( \ln B_0 \) is logarithm of bole area, in square feet per
acre.

\( R_{ps} \) is potential direct beam solar radiation re-
ceived during solar day on index date (March
21), in Langley's (Frank and Lee 1966).

The associated, descriptive statistics are:

\[ S_{y.x} = 0.83 \text{ inches} \]

where \( S_{y.x} \) is the standard error of estimate with mean
snowpack water content (WE) of 2.00 inches.

\[ r^2 = 0.58 \]

Volume. Inventory-prediction equations describing snowpack
water content at peak accumulation as a function of the volume of
forest cover were constructed only on the Campbell Blue study area
Again, the logarithmic model was selected as a forest cover base, to which potential direct beam solar radiation was added. The resulting equation follows:

\[ Y = 16.6 - 0.586 \ln V - 0.0148 R_{ps} \]  

where \( Y \) is snowpack water content (WE) representing peak accumulation, prior to spring runoff (March 15, 1969), in inches.

\( \ln V \) is the logarithm of volume, in cubic feet (Myers 1963b) per acre.

\( R_{ps} \) is potential direct beam solar radiation received during solar day on index date (March 21), in Langley's (Frank and Lee 1966).

The associated, descriptive statistics are:

\[ S_{y.x} = 0.84 \text{ inches} \]

where \( S_{y.x} \) is the standard error of estimate with mean snowpack water content (WE) of 2.00 inches.

\[ r^2 = 0.57 \]

Number of Trees in Relation to Height. Relationships between snowpack water content at peak accumulation and height-index, developed from only a subsample of plots on Campbell Blue (Table 16), were statistically similar to relationships describing the winter accumulation-melt period. As with the earlier measurement period,
Table 15

Inventory-Prediction Equations Describing Snowpack Water Content at Peak Accumulation, Prior to Spring Runoff, as a Function of Volume—Campbell Blue

<table>
<thead>
<tr>
<th>Equation Number</th>
<th>Equations</th>
<th>$s_{YX}$</th>
<th>r²</th>
<th>cp</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$Y = 2.91 - 0.634(10^{-3})V$</td>
<td>1.08</td>
<td>0.27</td>
<td>8.78</td>
</tr>
<tr>
<td>2</td>
<td>$Y = 1.54 + 207/V$</td>
<td>1.08</td>
<td>0.27</td>
<td>8.64</td>
</tr>
<tr>
<td>3</td>
<td>$Y = 2.23 - 0.947(10^{-7})V^2$</td>
<td>1.18</td>
<td>0.13</td>
<td>17.62</td>
</tr>
<tr>
<td>4</td>
<td>$Y = 7.63 - 0.812 \ln V$</td>
<td>0.98</td>
<td>0.40</td>
<td>0.77</td>
</tr>
<tr>
<td>5</td>
<td>$Y = 9.07 - 65.7/V - 0.999 \ln V$</td>
<td>0.99</td>
<td>0.41</td>
<td>2.39</td>
</tr>
<tr>
<td>6</td>
<td>$Y = 14.2 + 0.473(10^{-3})V - 201/V - 1.80 \ln V$</td>
<td>0.99</td>
<td>0.42</td>
<td>3.30</td>
</tr>
<tr>
<td>7</td>
<td>$Y = 19.7 + 0.00166V - 316/V - 0.148(10^{-6})V^2 - 2.75 \ln V$</td>
<td>0.99</td>
<td>0.43</td>
<td>5.00</td>
</tr>
</tbody>
</table>

Independent variable - $(Y)$ is snowpack water content (WE) representing peak accumulation, prior to spring runoff (March 15, 1969), in inches.

Dependent variable - $(V)$ is volume, in cubic feet (Myers 1963b) per acre.

(\ln V) is logarithm of volume, in cubic feet (Myers 1963b) per acre.

Mean snowpack water content (WE) of 2.00 inches.
Table 16

Inventory-Prediction Equations Describing Snowpack Water Content at Peak Accumulation, Prior to Spring Runoff, as a Function of Height-Index—Campbell Blue

<table>
<thead>
<tr>
<th>Equation Number</th>
<th>Equations</th>
<th>$S_{Y \cdot x}$</th>
<th>$r^2$</th>
<th>$cp$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple regressions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>$Y = 2.51 - 0.826 HI$</td>
<td>0.91</td>
<td>0.28</td>
<td>6.88</td>
</tr>
<tr>
<td>2</td>
<td>$Y = 0.0375 + 1.40/HI$</td>
<td>0.74</td>
<td>0.53</td>
<td>0.50</td>
</tr>
<tr>
<td>3</td>
<td>$Y = 1.85 - 0.182 HI^2$</td>
<td>0.97</td>
<td>0.18</td>
<td>9.75</td>
</tr>
<tr>
<td>4</td>
<td>$Y = 1.60 - 1.32 \ln HI$</td>
<td>0.82</td>
<td>0.43</td>
<td>3.26</td>
</tr>
<tr>
<td>Multiple regressions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>$Y = 0.832 + 2.16/HI$</td>
<td>0.75</td>
<td>0.55</td>
<td>2.05</td>
</tr>
<tr>
<td></td>
<td>$+ 0.854 \ln HI$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>$Y = 1.28 - 2.09 HI$</td>
<td>0.75</td>
<td>0.58</td>
<td>3.20</td>
</tr>
<tr>
<td></td>
<td>$+ 4.67/HI + 5.98 \ln HI$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>$Y = 5.60 - 15.1 HI$</td>
<td>0.78</td>
<td>0.59</td>
<td>5.00</td>
</tr>
<tr>
<td></td>
<td>$+ 9.32/HI + 1.59 HI^2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$+ 20.7\ln HI$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$a = 0.10, n = 16$

Dependent variable - (Y) is snowpack water content (WE) representing peak accumulation, prior to spring runoff (March 15, 1969), in inches.

Independent variable - (HI) is height-index (Larson and Minor 1968). (\ln HI) is logarithm of height-index (Larson and Minor 1968).

1 Mean snowpack water content (WE) of 1.60 inches.
the hyperbolic model was selected as a forest cover base, to which potential direct beam solar radiation was combined in a multiple regression. The resulting inventory-prediction equation follows:

\[ Y = 7.27 - 0.938/\text{HI} - 0.00938 \frac{R}{ps} \]  

where \( Y \) is snowpack water content (WE) representing peak accumulation, prior to spring runoff (March 15, 1969), in inches.

HI is height-index (Larson and Minor 1968).

\( R_{ps} \) is potential direct beam solar radiation received during solar day on index date (March 21), in Langley's (Frank and Lee 1966).

The associated, descriptive statistics are:

\[ S_{y,x} = 0.65 \text{ inches} \]

where \( S_{y,x} \) is the standard error of estimate with mean snowpack water content (WE) of 1.60 inches.

\[ r^2 = 0.66 \]

Spring Runoff

Quantifications of snowpack water content depletion during the spring runoff period as related to inventory-prediction variables may define forest-snow conditions necessary to maximize snow melt rates or minimize the length of the runoff period. These two hydrologic
criteria have been suggested (Garn 1969, Hansen and Ffolliott 1968) as objectives of land management systems designed to increase water yields derived from snow within the ponderosa pine type in Arizona.

Evaluations of snowpack dynamics during spring runoff were only made on the Beaver Creek study area. Snowpack measurements used to characterize this period were taken, as close as possible, to coincide with the time of peak daily runoff and still represent complete snowpack cover. This latter restriction was necessary to insure the maximum number of data points for analyses.

Two analytic approaches were followed in attempting to develop inventory-prediction equations for this period. Residual snowpacks were analyzed and incremental changes were evaluated. In both instances, stated regression procedures and constraints remained the same.

**Residual Snowpack.** Relationships between residual snowpack water content and basal area at the approximate time of peak daily runoff were not statistically significant in the two years of study on Beaver Creek. Consequently, multiple regressions combining basal area, potential direct beam solar radiation, and elevation were not constructed.

Basal area was the only forest cover variable analyzed in this snowpack measurement period. However, due to the consistency of
non-significance in previous measurement periods, it was assumed that relationships involving other forest cover variables would not be statistically significant here, either.

Residual snowpack water content at approximate peak daily runoff was statistically correlated with potential direct beam solar radiation (\( r = -0.541, n = 75 \) on March 3, 1968, and \( r = -0.564, n = 75 \) on March 29, 1969) in the two years of study. Snowpack water content was correlated with elevation (\( r = 0.275, n = 75 \) on March 29, 1969), and, consequently, with both potential direct beam solar radiation and elevation (\( r = 0.602, n = 75 \) on March 29, 1969) in one year of study.

**Snowpack Melt Index.** Incremental changes in snowpack water content between peak accumulation, prior to the start of spring runoff, and approximate time of peak daily runoff formed an index of melt rates. This index was used as a dependent variable in attempting to develop inventory-prediction equations describing snowpack depletions during spring runoff. However, as with residual snowpack conditions, this melt index was not correlated with basal area. Therefore, detailed inventory-prediction equations could not be synthesized.

This snowpack melt index was statistically correlated with potential direct beam solar radiation (\( r = 0.325, n = 75 \) in 1967-68, and \( r = 0.443, n = 75 \) in 1968-69) in the two years of study. Melt index was correlated with elevation (\( r = -0.216, n = 75 \) in 1968-69),
and, as a result, with both potential direct beam solar radiation and elevation \( (r = 0.473, n = 75 \text{ in } 1968-69) \) in one year of study.

**Storage-Duration Index.** The summation of snowpack water contents measured in successive surveys yields a storage-duration index (Wilm 1948), indicative of the integration of initial snowpack storage and subsequent melt rates. Maximum index values are obtained with large initial storage followed by slow melting, while low initial storage followed by rapid melting provides a minimum index.

A storage-duration index was developed in this study, summing snowpack water contents at peak accumulation, at a measurement period midway between peak accumulation and approximate peak daily runoff, and at approximate peak daily runoff. This index was used in attempting to identify conditions associated with different snowpack storage-melt interactions.

Storage-duration values were correlated, in simple regression, with basal area \( (r = -0.201, n = 75) \), potential direct beam solar radiation \( (r = -0.525, n = 75) \), and elevation \( (r = 0.197, n = 75) \) in the 1967-68 study year. These correlations indicated high index values, i.e., large initial snowpack storage followed by slow melting, to be associated with low basal area levels, low potential direct beam solar radiation values, and high elevation. Low index values, i.e., low initial storage followed by rapid melting, were associated with the opposite conditions.
The following inventory-prediction equation, considering all potential independent variables, was developed:

\[
Y = 0.00112 - 0.0163BA - 0.0433R_{ps} + 0.00894E
\]

where \( Y \) is the summation of snowpack water contents (WE) at peak accumulation, prior to spring runoff (February 10, 1968), at a measurement period midway between peak accumulation and approximate peak daily runoff (March 3, 1968), in inches.

\( BA \) is basal area, in square feet per acre.

\( R_{ps} \) is potential direct beam solar radiation received during solar day on index date (February 20), in Langley's (Frank and Lee 1966).

\( E \) is elevation, in feet.

The associated, descriptive statistics are:

\[
S_{y.x} = 5.54 \text{ inches}
\]

where \( S_{y.x} \) is the standard error of estimate with mean snowpack water content (WE) of 24.04 inches.

\[
r^2 = 0.31
\]

In 1968-69, storage-duration values were not statistically correlated with basal area. Storage-duration values were correlated
with potential direct beam solar radiation \( r = -0.478, n = 75 \), elevation \( r = 0.233, n = 75 \), and, consequently, with both variables \( r = 0.510, n = 75 \), however.

Residual Snowpack at the End of Spring Runoff

The distribution of the snowpack remaining at the end of the spring runoff period might indicate what land management practices should be implemented to capture this residual. Specifically, correlations between the residual snowpack and associated forest cover and site conditions could define land management systems designed to reduce water losses to factors other than runoff.

End of runoff analyses were limited to the Beaver Creek study area. It was not possible to measure this event in the one year of study on Campbell Blue, and data available from the S.C.S. Cooperative Snow Surveys could not be consistently associated with end of runoff.

In the two years of study on Beaver Creek, the residual snowpack at the end of the spring runoff period, representing less than 20 percent areal snowpack cover, remained in isolated drifts to the leeward of dense timber overstory or in some form of topographic shade. Unfortunately, no quantitative relationships between residual snowpack water content and any potential forest cover or site variable was
evident, preventing the development and evaluation of inventory-prediction equations. It was generally concluded, therefore, that definitive land management systems affecting these snowpack conditions could not be formulated.

**Snowpack Distribution as Related to Forest Cover Patterns**

Auxiliary analyses of snowpack distributions as related to discrete patterns of forest cover, defined by point sampling techniques, was carried out in attempting to determine what relationships, if any, existed between the snowpack and forest cover juxtaposition. The results of these analyses, when statistically significant, were consistent with previous studies (Ffolliott and Hansen 1968, Wilm and Collet 1940), indicating snowpack water content to increase with distance from surrounding trees.

**Quantifying Forest Cover Patterns**

As mentioned above, sample trees were selected at individual sample points by using an angle gage corresponding to basal area factors of 25 (the mensurational base), 50, 75, and 100. Using this array of basal area factors, and evaluating each tree in terms of being tallied or not being tallied with the individual basal area factors, it is possible to diagrammatically describe the spatial arrangement of trees surrounding a sample point.
The maximum distance (in feet) that a tree tallied with a given basal area factor can be from a sample point is the product of the plot radius factor (feet per inch of tree diameter) and the tree diameter (in inches). The plot radius factor is a constant (Beers and Miller 1964, Dilworth and Bell 1958, Grosenbaugh 1955) uniquely associated with each specified basal area factor. A plot radius factor is computed as follows:

\[
PRF = \frac{8.696}{\sqrt{BAF}}
\]

where \(PRF\) is the plot radius factor associated with the specified basal area factor (BAF), in feet.

It is obvious that the smaller the basal area factor, the larger the plot radius factor. Therefore, the smaller the basal area factor, the greater is the distance a tallied tree can be from a sample point.

Trees tallied exclusively with a small basal area factor (25) can be further from a sample point than trees tallied with additional larger basal area factors (50, 75, etc.). For example, assume that three 10-inch trees are tallied with a basal area factor of 25 at a sample point. The maximum distance that the three trees can be from the point is 17.4 feet, the product of 1.74, the plot radius factor associated with a basal area factor of 25, and 10, the diameter of the tallied trees.
Now, additionally, assume that one of the three trees is also tallied with basal area factors of 50, 75, and 100. The maximum distance that the tree tallied with a basal area factor of 50 can be from the point is 12.3 feet, the product of 1.23, the plot radius factor, and 10, the tree diameter. The maximum distance that the tree tallied with basal area factors of 50, 75, and 100 can be from the point is 8.7 feet, the product of 0.87, the plot radius factor associated with the largest basal area factor (100) used in the inventory, and 10, the tree diameter.

Knowing individual sample point tree tallies in relation to all of the basal area factors used in an inventory allows the trees to be identified in terms of maximum distances from the point. The trees can then be schematically located within concentric circular plots delineated by radii defined by the maximum distance values. This spatial arrangement can only be approximated. Intermingling of trees of different diameters will cause an overlapping of concentric circular plots circumscribed by a given basal area factor. Also, it is not normally possible to orient trees with respect to cardinal directions using a tree tally at a sample point. However, even if approximated, classifying sample points in accordance with tree tallies in relation to different basal area factors would identify similar discrete forest cover patterns.
The individual sample points comprising the primary sampling units in this study, although systematically located internally, were assumed to be representative of independent sampling units in these analyses. It was felt that the spatial arrangement of the forest cover surrounding a point was not necessarily dependent on the spatial arrangement surrounding adjacent points.

Accepting the hypothesis of independence, the individual sample points on Campbell Blue and Beaver Creek, the two study areas analyzed, were classified with regard to forest cover patterns defined by point sampling with an angle gage corresponding to basal area factors of 25, 50, 75, and 100 as follows:

1. No trees tallied with a basal area factor of 25, i.e., all trees a distance (in feet) greater than 1.74 times tree diameter from sample point. This forest cover pattern represents a density level of less than 25 square feet of basal area per area.

2. Trees tallied exclusively with a basal area factor of 25, i.e., all tallied trees a distance (in fact) between greater than 1.23 and equal to 1.74 times tree diameter from sample point. This forest cover pattern represents a density level of at least 25 but less than 50 square feet of basal area per acre.

3. Trees tallied with a basal area factor of 25 with at least one tree additionally tallied exclusively with a basal area factor of
50, i.e., all tallied trees at least a distance (in feet) between greater than 1.00 and equal to 1.74 times tree diameter from sample point, with at least one tree between greater than 1.00 and equal to 1.23 times tree diameter from sample point. This forest cover pattern represents a density level of at least 50 but less than 75 square feet of basal area per acre.

4. Trees tallied with a basal area factor of 25 with at least one tree additionally tallied exclusively with basal area factors of 50 and 75, i.e., all tallied trees at least a distance (in feet) between greater than 0.87 and equal to 1.74 times tree diameter from sample point, with at least one tree between greater than 0.87 and equal to 1.00 times tree diameter from sample point. This forest cover pattern represents a density level of at least 75 but less than 100 square feet of basal area per acre.

5. Trees tallied with a basal area factor of 25 with at least one tree additionally tallied exclusively with basal area factors of 50, 75, and 100, i.e., all tallied trees at least a distance (in feet) between at least 0.87 and equal to 1.74 times tree diameter from sample point, with at least one tree between at least 0.87 and equal to 1.00 times tree diameter from sample point. This forest cover pattern represents at least 100 square feet of basal area per acre.
A total of 200 individual sample points on Campbell Blue and 375 individual sample points on Beaver Creek, each study area being analyzed separately, provided the computational basis.

Snowpack Distribution

Analyses and descriptions of snowpack distributions as related to discrete forest cover patterns were restricted to conditions at peak accumulation, primarily because of the significance of this event in estimating potential water yields. Analyses of variance and, when appropriate, Tukey's multiple comparison test were employed to identify statistically significant differences between peak accumulation snowpack water content and patterns of forest cover.

Generally, on the Campbell Blue study area, a greater snowpack water content was measured at sample points located away from trees, indicating low forest cover densities, than at sample points close to trees, which indicate high forest cover densities. An average snowpack water content of 4-1/2 inches was measured at sample points characterized by no trees tallied with a basal area of 25, while less than two inches snowpack water content was measured at sample points where at least one tree was tallied with a basal area factor of 100. Intermediate snowpack water contents were measured at sample points where trees were tallied with basal area factors of 25, 50, and 75.
The greatest difference in snowpack water contents between forest cover patterns on Campbell Blue (Table 17) occurred when comparing sample points where no trees were tallied with a basal area factor of 25 with the other defined forest cover patterns. An increase of approximately two inches in snowpack water content was realized when comparing the former sample points with the latter. Differences in snowpack water contents among sample points where trees were tallied with at least one of the basal area factors used in this study were of a lesser magnitude.

It would appear that, based on the Campbell Blue analysis, peak snowpack accumulation gains would be greatest, within the study framework, at forest cover density levels of less than 25 square feet of basal area per acre, as compared with gains among any of the other defined density levels. However, as will be discussed below, whether this apparent gain in peak accumulation was a net increase relative to the entire snowpack could not be determined.

Relationships between snowpack water contents and distances between sample points and adjacent trees were inconsistent in the two years of study on Beaver Creek. Differences in average snowpack water contents among the forest cover patterns were small, limiting interpretations.

In 1967-68, a statistically significant difference in snowpack water contents was observed (Table 18) when comparing sample points
Table 17

Snowpack Water Content at Peak Accumulation, Prior to Spring Runoff, as Related to Discrete Forest Cover Patterns--Campbell Blue

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Degrees of Freedom</th>
<th>Sums of Squares</th>
<th>Mean Squares</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Among sample</td>
<td>4</td>
<td>176.95</td>
<td>44.24</td>
<td>17.34*</td>
</tr>
<tr>
<td>Error</td>
<td>195</td>
<td>494.80</td>
<td>2.55</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>199</td>
<td>671.75</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Tukey's Test, \( a = 0.10 \)**

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>BAF 25</th>
<th>BAF 50</th>
<th>BAF 75</th>
<th>BAF 100</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAF 100</td>
<td>2.88</td>
<td>0.93</td>
<td>0.77</td>
<td>ns</td>
<td>0</td>
</tr>
<tr>
<td>BAF 75</td>
<td>2.03</td>
<td>1.09</td>
<td>0.93</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>BAF 50</td>
<td>2.11</td>
<td>ns</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BAF 25</td>
<td>1.95</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 18

Snowpack Water Content at Peak Accumulation, Prior to Spring Runoff, as Related to Discrete Forest Cover Patterns—Beaver Creek (1967-68)

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Degrees of Freedom</th>
<th>Sums of Squares</th>
<th>Mean Squares</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Among sample</td>
<td>4</td>
<td>89.18</td>
<td>22.30</td>
<td>5.45*</td>
</tr>
<tr>
<td>Error</td>
<td>370</td>
<td>1514.53</td>
<td>4.09</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>374</td>
<td>1603.71</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tukey's Test, $a = 0.10$

<table>
<thead>
<tr>
<th>Differences of Means</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>BAF 100</td>
</tr>
<tr>
<td>BAF 75</td>
</tr>
<tr>
<td>BAF 50</td>
</tr>
<tr>
<td>BAF 25</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>
where no trees were tallied with a basal area factor of 25 with sample points where at least one tree was tallied with a basal area factor of 100. Little meaning could be attached to the other differences, however.

Although statistical differences did occur in the 1968-69 analysis (Table 19), inconsistency in the data prevented interpretations.

The causal reasons for differences in snowpack distributions as related to forest cover patterns can only be intuitively evaluated in this study. It is difficult to question the fact that forest cover intercepts falling snow, thereby preventing immediate accumulation on the ground surface. However, it is not possible to know whether the larger snowpack water contents measured away from timber overstory represents a net gain to the snowpack in terms of potential water yields, or, conversely, whether the smaller snowpack water contents measured near or under timber overstory is a loss.

Snowpack differences between sites under forest cover and in the open, as was observed on Campbell Blue and Beaver Creek, have often been attributed to an interception loss (Baldwin 1957, Connaughton 1935, Dunford and Niederhof 1944, Packer 1962, Rowe and Hendrix 1951, Urie 1966, Wilm and Dunford 1948). Undoubtedly, the theoretical potential for snowpack interception losses may exist (Leonard and Eschner 1968, Miller 1966, Satterlund and Eschner 1965). However,
Table 19
Snowpack Water Content at Peak Accumulation, Prior to Spring Runoff, as Related to Discrete Forest Cover Patterns--Beaver Creek (1968-69)

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Degrees of Freedom</th>
<th>Sum of Squares</th>
<th>Mean Squares</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Among samples</td>
<td>4</td>
<td>240.45</td>
<td>60.11</td>
<td>6.90*</td>
</tr>
<tr>
<td>Error</td>
<td>370</td>
<td>3222.60</td>
<td>8.71</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>374</td>
<td>3463.05</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tukey's Test, \( a = 0.10 \)

<table>
<thead>
<tr>
<th>Differences of Means</th>
<th>0</th>
<th>BAF 25</th>
<th>BAF 50</th>
<th>BAF 75</th>
<th>BAF 100</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAF 100</td>
<td>ns</td>
<td>2.09</td>
<td>1.32</td>
<td>ns</td>
<td>0</td>
</tr>
<tr>
<td>BAF 75</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>0</td>
</tr>
<tr>
<td>BAF 50</td>
<td>ns</td>
<td>ns</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>BAF 25</td>
<td>ns</td>
<td></td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td></td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
differences in snowpack water content measurements do not necessarily
directly prove interception losses (Hoover 1960, Sartz 1969), but
rather may index the ultimate deposition of snow inputs (Goodell 1963)
at a point in time.

It has been suggested (Miller 1966, Satterlund and Haupt 1968,
as cited by Copeland 1969) that a large portion of intercepted snow
may eventually reach the ground by different processes of transport
from trees, and that only a small portion is lost by vaporization. It is
probable (Lejcher 1969) that the forest cover canopies may reach a
point of maximum snow interception (Satterlund and Haupt 1967) many
times during heavy snow falls, with mass release, wind erosion, and
drip processes (Miller 1966) freeing the tree crowns of the excessive
loads. The net effect of the removal and transport of intercepted snow
may be a redistribution of snow from tree crowns to adjacent openings
(Hoover and Leaf 1967), which could result in no significant losses
in the water budget.

Casual observations made on Campbell Blue and Beaver Creek
indicated that a large portion of snow was often transported from
forest cover canopies into adjacent openings in the timber stand soon
after cessation of precipitation. The transport of snow, primarily
caused by sliding bodies of intercepted snow, wind erosion, and drip­
ning of melt water (Miller 1966), resulted in a redistribution of snow
around individual trees. This snowpack redistribution pattern appeared to be dependent, in part, on the crown characteristics and height of the individual trees, the spatial arrangement of the forest cover, and the prevailing winds.

Trees with dense, well-developed crowns had a greater potential capacity to intercept and retain falling snow than trees with small, sparse crowns. Snow intercepted in tall trees had greater distances to be transported, assuming the ultimate deposition to be on the ground, than snow intercepted in shorter trees. This differential in transported distance allowed snow intercepted in tall trees to be deposited at distances farther away from the tree. Spatial arrangements of high forest cover density levels meant transported snow was frequently intercepted by another tree before accumulating on the ground, which often resulted in a uniform redistribution of the snowpack somewhat independent of the forest cover. Finally, the prevailing winds following precipitation events greatly determined the major directions of snow transport, affecting redistribution.

The integrated effects of the above interactions among snow interception, snow transport, and forest cover exerted a large influence on the snowpack distributions on Campbell Blue and Beaver Creek. To what extent vaporization loss of intercepted snow contributed to these distributions could not be determined.
FOREST-SNOW PREDICTION TECHNIQUES AND MANAGEMENT GUIDELINES

Forest-snow prediction techniques and management guidelines applicable to the ponderosa pine type in Arizona can be constructed from the inventory-prediction data developed in this study. Although limited by the forest cover and site characteristics of the study areas, the different measurement and analysis objectives among the study areas, and the particular precipitation patterns in the years of study, the techniques and guidelines described may provide decision-making tools useful in evaluating resource-oriented multiple use conflicts involving the development of operational water yield improvement programs.

Prediction Techniques

The inventory-prediction equations developed serve two general snowpack prediction objectives: (1) to estimate the mean snowpack water content on a basin, and (2) to describe the trade-off, or the rate of exchange, between snowpack water content and forest-site variables on a decision-making land management unit. These two prediction objectives, although mutually exclusive regarding interpretation, can be satisfied simultaneously, yielding information helpful in the
formulation of effective and efficient water improvement land management systems.

Mean Snowpack Water Content on a Basin

Originally, it was thought that the mean snowpack water content on a basin, not necessarily being concerned with distribution, could be expressed as a function of precipitation, forest cover, and site variables. However, analyses of long-term records available from the S.C.S. Cooperative Snow Surveys indicated that precipitation was the only statistically significant variable.

Snowpack water content at peak accumulation, prior to spring runoff, was highly correlated with total precipitation inputs two months prior to the measurement date, and, consequently, an inventory-prediction equation (Equation 6, page 86) was developed. Estimates of mean snowpack water content at peak accumulation on a basin can be made with this equation.

A more general inventory-prediction equation can be constructed, however, allowing wider application in quantifying snowpack conditions. This equation describes snowpack water content at any point in time throughout the accumulation period, again using total precipitation inputs two months prior to the date of estimation as the independent variable. The equation, based on 217 measurement events occurring on 18 snow courses, follows:
\[ Y = 0.26 + 0.821 P_i \] (11)

where \( Y \) is snowpack water content (WE) at any point in time throughout the accumulation period, in inches.

\( P_i \) is total precipitation inputs two months preceding the date of estimation, in inches.

The associated, descriptive statistics are:

\[ S_{y.x} = 1.86 \text{ inches} \]

where \( S_{y.x} \) is the standard error of estimate with mean snowpack water content (WE) of 5.91 inches.

\[ r^2 = 0.71 \]

This equation can be used to estimate mean snowpack water content throughout the snowpack accumulation period on basins within the limits of the forest cover and site conditions sampled (Table 3). This equation is not necessarily valid once snow melt has begun, however, because other variables not measured in this study may influence these snowpack conditions.

**Trade-Off Coefficients on a Decision-Making Unit**

Most of the inventory-prediction equations developed in this study, specifically on Campbell Blue and Beaver Creek, quantify one
year of data. Therefore, the equations are strictly applicable only for a precipitation input similar to the year of study. However, predicting the magnitude of snowpack water content over time is not the objective here, but rather defining the trade-off between snowpack water content and forest-site variables on a decision-making unit.

Development of Trade-Off Coefficients. The development of trade-off coefficients is based, in part, on the hypothesis that, given a precipitation input, the distribution of snowpack water content is basically determined by forest cover and site. In other words, the relationship between snowpack distributions and forest-site variables is independent of precipitation. Assuming the independence of precipitation, exceptions being extremes in precipitation amounts, trade-off's between the snowpack and forest cover and site can be quantified within the framework of the inventory-prediction equations.

The development of trade-off coefficients is based on the following assumptions regarding the inventory-prediction equations:

1. The mathematical models selected to describe snowpack dynamics as functions of forest cover and site are appropriate.

2. The regression intercept values reflect the precipitation input in the year of study. Regression intercepts can be expected to vary with different precipitation inputs.
3. The regression coefficient values which, by definition, are trade-off coefficients will remain statistically constant with varying precipitation inputs. Unfortunately, the above assumptions can not be adequately substantiated with the short duration of data collection on the Campbell Blue and Beaver Creek study areas. However, an indication of their validity can be obtained through supplementary analyses of the long-term data available from the S.C.S. Cooperative Snow Surveys.

The development of trade-off coefficients based on the S.C.S. Cooperative Snow Survey data was restricted to relationships between snowpack water content at peak accumulation and forest cover, the latter variable expressed in terms of basal area. The limited sample size, only 18 snow courses were evaluated, prevented detailed analyses of site variables. Snow courses were analyzed individually because of discontinuities in forest cover density levels among the courses. Also, these discontinuities in density levels resulted in different trade-off coefficients among snow courses, as will be discussed below. However, the objective of these analyses was to evaluate internal changes in trade-off models as they may be attributed to time, not to illustrate similarities in trade-off coefficients among snow courses.
Regressions describing relationships between snowpack water content for each year of record and basal area were developed, the output being a family of regressions, which assumed a basic linear model, characterizing each course. The individual regression coefficients, were then evaluated with respect to statistical similarities.

Of the 18 snow courses in the sample, nine possessed a family of regressions in which no single regression coefficient was statistically significant. With all regression coefficients being equivalent to zero (0), the assumption of regression coefficients remaining constant was seemingly upheld. The families of regressions did differ in the intercept values (Figure 9), which was attributed to varying precipitation inputs among years.

The families of regressions characterizing the remaining nine snow courses in the sample exhibited at least one statistically significant regression coefficient. Families of regressions on three of these courses possessed both statistically significant and non-significant regression coefficients. These courses were dropped from further evaluations, and were considered not to support the assumptions behind the development of trade-off coefficients.

Families of regressions characterizing the remaining six snow courses were analyzed for statistical similarities among regression coefficients. With the exception of years with low precipitation input,
Figure 9. Family of Regressions Illustrating Relationship between Snowpack Water Content at Peak Accumulation for Different Years of Record (1958-67) and Basal Area on the Mormon Lake S.C.S. Cooperative Snow Survey Plot
i.e., total winter precipitation less than one-third of the long-term average, families of regressions on three courses were similar in terms of statistically equivalent regression coefficients. These three courses appeared to support the assumption of constant regression coefficients. The regression intercept values differed on these courses (Figure 10), but, again, this was attributed to varying precipitation inputs.

On two snow courses, regression coefficients defining two-thirds of the regressions in the respective families were statistically equivalent, while regression coefficients defining one-half of the regressions were statistically similar on the other course. These three courses were considered inconclusive regarding substantiation of the assumptions behind the development of trade-off coefficients.

Generally, 12 of 18 snow courses evaluated in the analyses appeared to support the basic assumptions used to define the trade-off between snowpack water content and forest variables. Admittedly, more testing will be required before the assumptions become fact. However, until proven otherwise, these assumptions will be accepted in this study, and the inventory-prediction equations will be used to develop trade-off coefficients.

**Specific Trade-Off Coefficients.** As forest cover is the only variable evaluated in the inventory-prediction equations that can be manipulated in water improvement programs, emphasis will be placed
Figure 10. Family of Regressions Illustrating Relationship between Snowpack Water Content at Peak Accumulation for Different Years of Record (1958-67) and Basal Area on the Canyon Creek S.C.S. Cooperative Snow Survey Plot
on the trade-off between snowpack water content and expressions of forest cover. Knowledge of these trade-off coefficients may help to formulate land management practices designed to increase water yields.

Inventory-prediction equations developed in this study describe snowpack dynamics as a simple function of forest cover (Tables 4, 5, etc.), and as functions of both forest cover and site variables (Equation 1, page 70, Equation 2, page 74, etc.). For illustrative purposes, only simple regressions will be considered here. This does not imply that multiple regressions, which describe relationships between snowpack dynamics and forest cover over a range of sites, would not serve equally as well.

Examples of trade-off coefficients can be derived from inventory-prediction equations describing snowpack water content at peak accumulation, prior to spring runoff. Considering basal area, bole area, and volume as expressions of forest cover density, logarithmic transformations were selected as the appropriate mathematical models (Tables 10, 14, and 15). Regression coefficients defining these logarithmic equations, and, by definition, trade-off coefficients, are $-1.05 \ln BA$, $-0.887 \ln BO$, and $-0.812 \ln V$, respectively. Solving these coefficients for incremental changes in forest cover density values will define corresponding changes in the snowpack.
Essentially, trade-off coefficients define a fundamental rate of exchange between snowpack water content and, in the above case, expressions of forest cover density. When a curvilinear model is selected, the quantity of the trade-off will vary with respect to the particular forest cover incremental values selected for solution. A linear model produces a constant trade-off throughout. If a linear model is similar to a curvilinear model in terms of the standard error of estimate, coefficient of determination, etc., as is the case with basal area in the above example (Table 10), the linear model could be used as a substitute to ease interpretation.

Trade-off coefficients can be obtained from other inventory-prediction equations describing different snowpack conditions, if desired. Solving these coefficients for incremental changes in forest cover density dictated by management objectives will, again, define corresponding changes in snowpack water content.

All of the potential trade-off coefficients derived for a particular snowpack measurement period are not statistically equivalent, at least in terms of the standard error of estimate, coefficient of determination, etc. Some expressions of forest cover density, i.e., basal area, bole area, volume, and height-index, appear generally better than others, i.e., point density, sum of diameters, and number of
trees. Also, some expressions are more readily computed from input data, i.e., basal area and volume, than others, i.e., bole area and height-index. Furthermore, certain expressions may be a necessary requirement to prescribe and implement a land management system. The ultimate choice of a trade-off coefficient must be made with these considerations in mind.

As the extent of applicability of the inventory-prediction equations developed in this study is largely unknown, the extent of applicability of the derived trade-off coefficients is not known, either. It is anticipated that additional testing and evaluation will be necessary before widespread acceptance is achieved. This study does provide a point of departure for subsequent investigations, however.

Prediction Model for a Decision-Making Unit

A primary use of the inventory-prediction data developed in this study is to predict increases in snowpack water yield on a decision-making unit resulting from the implementation of proposed land management systems. However, inventory-prediction data alone may not define changes in recoverable water yield. Nonbiotic characteristics of the land, which may not be altered by management programs consisting of vegetation manipulations, must also be considered. These characteristics include topographic features, geographic and geologic formations, soil properties, etc.
It is conceivable that nonbiotic characteristics could dictate water yield to the extent that the predicted changes defined by the inventory-prediction data could be masked. That this could happen can best be illustrated by an example formulated within the framework of a conceptual model developed to evaluate proposed land management systems designed to increase water yield. The evaluation model, which attempts to identify the components in a dynamic, water yielding situation, follows:

\[ R_{0t} = R_0 + (ROP)(ROE) \]

where \( R_{0t} \) is estimated snowpack water yield following implementation of a land management system designed to increase snowpack water yield, expressed in terms of surface runoff.

\( R_0 \) is existing snowpack water yield, in terms of surface runoff. This value is a time-weighted average indicative of the mean annual snowpack water yield.

\( ROP \) is the predicted change in snowpack water yield on the decision-making unit, determined from analyses of trade-off coefficients derived from the inventory-prediction equations.
ROE is runoff efficiency, defined as the portion of the snowpack water content at peak accumulation, prior to spring runoff, that is converted into surface runoff by the end of the runoff period (Garn 1969, Thorud 1969). This value is determined by the vegetative and nonbiotic characteristics of the land, and may be dynamic in terms of changes due to the impact of land management re-direction, antecedent moisture, etc.

To illustrate the application and interpretation of the evaluation model, assume that a uniform thinning of the forest cover is proposed as a land management system designed to increase snowpack water yield. Specifically, let the management system call for a reduction in timber overstory density from the existing 150 to a projected 50 square feet of basal area per acre.

The existing snowpack water yield \((R_{00})\) on the land unit in question, measured by surface runoff, is given as 5.0 area-inches. Assume that the runoff efficiency \((ROE)\) is 0.90, i.e., 90 percent of the snowpack water content at peak accumulation is converted to surface runoff.
Utilizing the proper trade-off coefficient, -0.105 lnBA (Table 10), and solving this coefficient for the specified incremental change in basal area density, a predicted change in snowpack yield (ROP) is obtained as follows:

\[
ROP = 1.05(\ln BA_t) - (-1.05(\ln BA_0))
\]

where ROP is defined as above.

\(BA_t\) is projected basal area density level following implementation of the land management system, in square feet per acre.

\(BA_0\) is existing basal area density level, in square feet per acre.

Therefore, substituting above gives:

\[
ROP = -1.05(\ln 50) - (-1.05(\ln 150))
\]

\[
= 1.2 \text{ inches}
\]

Adding the predicted change in water yield (ROP) to the existing water yield (\(R_0\)) gives an estimated water yield of 6.2 inches following implementation of the system. This estimate, which does not consider runoff efficiency, is similar to an estimate derived by solving the evaluation model with the above input data.

\[
R_{0t} = 5.0 + (1.2)(0.90)
\]

\[
= 6.1 \text{ inches}
\]
The relative agreement between the two estimates of water yield following implementation of the system is attributed to the high runoff efficiency assumed. But, imagine that the land unit is actually characterized by a runoff efficiency of 0.20. Solving the evaluation model results in quite a different estimate of water yield following implementation.

\[ R_{0t} = 5.0 + (1.2)(0.20) \]

\[ = 5.2 \text{ inches} \]

In this case, the estimate developed without considering the runoff efficiency is not approximated by the estimate derived from the evaluation model. The causal reason for the discrepancy, obviously, is the low runoff efficiency now assumed to characterize the land unit.

It can readily be seen that the estimated snowpack water yield following implementation of a land management system is dependent on two factors: (1) the predicted change in snowpack water yield on a decision-making unit, and (2) the inherent runoff efficiency characterizing the land. The inventory-prediction techniques developed in this study provide information only to predict changes on a decision-making unit. The determination of runoff efficiency values is considered a separate problem. However, as will subsequently be discussed, it is possible to construct management guidelines within the context of the predicted changes on a decision-making unit without considerations of runoff efficiency.
Management Guidelines

Often, management guidelines useful in formulating resource-oriented land management systems are nothing more than rules of thumb which, hopefully, allow the land manager to implement effective and efficient practices and procedures. As it may be difficult to attain the absolute point of optimum effectiveness and efficiency in a dynamic situation, these rules of thumb attempt to identify the right direction that management should proceed to realize optimization and indicate what gains and sacrifices will occur.

The management guidelines developed in this study are essentially rules of thumb which provide decision-making criteria for use in formulating and implementing land management systems designed to increase snowpack water yield by thinning forest cover. No attempt will be made to provide information on water yield improvement programs consisting of clearing forest cover, preventing comparisons between the two primary options available to land managers for vegetation manipulations. Although primary consideration will be given to increasing recoverable water, the guidelines constructed here will be developed within the framework of determining the multiple use effects on all the major forest-based products.
Decision-Making Land Management Unit

Obviously, land management can not influence the basic precipitation input to the land, and, consequently, may not effect the mean snowpack water content on a basin. Land management involving the thinning of forest cover may cause a redistribution of the snowpack, possibly increasing water yield from a given precipitation input by increasing efficiency of delivery of water to stream courses and groundwater storage (Hoover and Leaf 1967, Sartz 1969). The management guidelines to be developed are assumed to evaluate this latter phenomenon in terms of trade-off coefficients between snowpack water content and forest cover on a decision-making unit.

Definitions. A decision-making unit is the basic unit of management planning and implementation, as arbitrarily defined by the land manager. It may be defined silviculturally, such as a unit area (Hallin 1959), a homogeneous forest element characterized by age, density, size class composition, etc. This specific definition has direct application in describing the mosaic patterns of the ponderosa pine type in Arizona (Cooper 1961, Curtis and Lynch 1957, Pearson 1950).

Ecologically, decision-making units may be delineated as ecological communities (Ripley and Yandle 1969), with each community capable of uniform response to a given land management re-direction.

In terms of hydrologic criteria, a decision-making unit could be defined as a hydrologic stratum (Miller 1969), a subwatershed area.
homogeneous in hydrologic characteristics and water yield potential. It could be a hydrologic complex (Rowe 1943), an area expected to react uniformly in water yield to a specific hydrologic land treatment. Or, it could be a unit-source area (Amerman 1965), a subdivision of a complex watershed having a single forest cover, single soil type, and otherwise physically homogeneous.

Economically, a technical unit (Heady 1952), which is a unit of fixed factor (land) for which the production function can be calculated may define a decision-making unit.

Considering multiple use planning, a decision-making unit may be a resource zone (Tackle 1968), which delineates broad areas with similar resource combinations and management opportunities.

Management guidelines should identify the hydrologic potentials (Anderson 1967a) on a decision-making unit, however defined, in terms of snowpack water yield under present and possible future land management systems.

Limitations of Experimental Watershed Data. Changes in mean estimates of recoverable water yield on a basin attributed to forest cover manipulations on experimental watersheds (Brown 1969b, Hewlett and Hibbert 1961, Hibbert 1967, Reinhart 1965) do not necessarily lend themselves to the construction of sophisticated land management guidelines. The frequent lack of knowledge regarding runoff efficiency values
prohibits solving the evaluation model in terms of estimating water yield following the implementation of a proposed land management system. Even when known, if variable in time and space (Table 20), runoff efficiency can seriously limit the applicability of experimental watershed data.

The results available from experimental watersheds may be unique case histories, making the translation of results to an operational unit difficult (Hewlett, Lull, Reinhart 1969). Changes in water yield on experimental watersheds can perhaps be expressed in terms of ranked response for extrapolation purposes, but defining quantitative response may be questionable. What happens on experimental watersheds has generally been determined, while how and why have not (Dils 1967). Considering the limitations, it would seem as though experimental watersheds have little value in the development of management guidelines or as basic decision-making units.

In this study, emphasis will be placed on developing management guidelines sensitive to predicted changes in water yields on a decision-making unit, again, however defined, as an alternative to results obtained from changes in water yield on experimental watersheds. The management guidelines will outline changes in snowpack water content occurring on site as opposed to changes in water yield expressed as surface runoff. It will be assumed that, by maximizing snowpack water content on site, the maximum water yield in surface runoff may be achieved.
Table 20

Peak Snowpack Accumulation, Total Runoff, and Runoff Efficiencies for Different Beaver Creek Watersheds

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Year</th>
<th>Peak Snowpack Accumulation</th>
<th>Total Surface Runoff</th>
<th>Runoff Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>1966</td>
<td>3.36 Inches</td>
<td>3.08 Inches</td>
<td>93 Percent</td>
</tr>
<tr>
<td>15</td>
<td>1968</td>
<td>8.50 Inches</td>
<td>1.70 Inches</td>
<td>18 Percent</td>
</tr>
<tr>
<td>15</td>
<td>1969</td>
<td>5.72 Inches</td>
<td>1.64 Inches</td>
<td>28 Percent</td>
</tr>
<tr>
<td>17</td>
<td>1969</td>
<td>5.55 Inches</td>
<td>3.70 Inches</td>
<td>56 Percent</td>
</tr>
</tbody>
</table>

Adapted from Thorud (1969).
Management Guideline Models

Attempts will be made to describe management guidelines necessary to allow snowpack water content on site and, presumably, the potential for increasing recoverable water to be maximized. These water-oriented guidelines will be formulated within constraints dictated by land management involving the other forest-based products, however. While water is currently considered a limiting factor to aspects of future long-range physical and economic growth in Arizona, an expanding population may also demand other forest-based products obtained from upstream land areas. It is conceivable that a major breakthrough in water supply fields could make one of these other products replace water as the limiting factor in the future. It will be assumed, therefore, that production of all major forest-based products must proceed, so the ultimate land management system must consider the total product-mix.

Specific management guideline models to be formulated, based on the inventory-prediction equations and trade-off coefficients for the Campbell Blue study area, will describe snowpack water content at peak accumulation, prior to spring runoff. This quantity, theoretically, represents the best estimate of the potential for recoverable water derived from snow. Forest cover density expressions to be considered are basal area, because of wide acceptance and linkage with other forest-based products, and volume, because of implications in economic evaluations.
Site, which places the models into n-dimensions, will be held constant, with the models developed assumed representative of the site measured.

Management guidelines involving other snowpack conditions and different expressions of forest cover density can similarly be developed as those illustrated here.

**Basal Area.** Solving the appropriate trade-off coefficient, -1.05 \( \ln(BA) \) (Table 10), in terms of the incremental change in basal area density levels proposed by a management re-direction allows corresponding gains in snowpack water content on site to be determined. Generally, little meaning is attached to the regression intercept in the inventory-prediction equation, changes in snowpack water content being expressed as gain referenced by a threshold value representing existing basal area density levels.

The existing basal area density level can be defined as the mean value on a decision-making unit, if density is normally distributed about the mean. However, if skewed from normality, which is common with ponderosa pine in Arizona, a weighted mean may be required. Similarly, projected density level following implementation may either be a simple or weighted mean, depending on whether the proposed management system approaches even-aged, even-distributed timber conditions.

The greatest gain in snowpack water content occurs when high forest cover density levels are reduced to low density levels. Complete
flexibility in realizing this objective is not always possible because constraints dictated by the management of other forest-based products may limit the options available to the land manager. This can best be illustrated by rules of thumb developed for the management of timber and range products obtained from the ponderosa pine type of Arizona. Although constraints imposed by the management of other resources may also limit options, direct returns to the land as derived from timber and range products can be more easily evaluated at the present time.

Initially, plotting the specified inventory-prediction equation allows a skeletal guideline model to be constructed to which the management constraints will be added. As this is a general model without a reference point indicating an existing forest cover density level, the regression intercept value can be used to orient the trade-off between snowpack water content and basal area.

Snowpack water content and basal area exhibit a competitive relationship throughout the range of available data used in plotting the skeletal model. A competitive relation exists between products such that one must be sacrificed (timber) to gain more of another (water). Timber and range production constraints essentially place sideboards on this competitive relationship, with the maximum gain in snowpack water content dependent upon the most limiting constraint.
Timber production constraints assume that a minimum forest cover density will be required to maintain productivity in light of existing and projected growth rates and market outlets (Shupe 1965, Spencer 1966, Wilson and Spencer 1967). This constraint may vary, with considerations given to local silvicultural practices and demands placed on local wood products. It is also a dynamic constraint, reflecting improvements and changes in growth rates and market outlets with time.

A commercial timber production constraint is commonly expressed as a minimum annual growth per acre. This minimum, as given by the U. S. Forest Service (Blyth, Kallio, Callahan 1969, U. S. Forest Service 1963), is 20 cubic feet per acre, depending on site quality and density conditions. Conversion of cubic feet of growth to square feet of basal area for use in this model depends on the growth percent (Davis 1954) and the intermingling of tree volumes and size classes. With the growth percent and intermixture of size classes and volumes measured on the Campbell Blue and Beaver Creek study areas, an average basal area density of 35 to 40 square feet per acre would represent the minimum allowable production level for timber.

Range constraints are usually stated in terms of a minimum annual forage productions level, with production below this level being considered waste range. In Arizona, this minimum production level is specified as 50 pounds dry-weight of forage per acre by the U. S. Forest
Service (U. S. Forest Service 1960). To evaluate this value within the context of the management model, it is necessary to determine what forest cover densities limit forage production to this level. Using herbage production and timber overstory relationships applicable to the ponderosa pine type in Arizona (Clary and Ffollott 1966, Clary 1969), densities in excess of 160 square feet of basal area per acre would appear to restrict forage production to waste range.

Combining the skeletal model with the timber and range constraints described above results in the basic management guideline model (Figure 11) for decision-making purposes. Acceptable management possibilities for increasing snowpack water content lie between these two constraints. Management to the left of the timber constraint (T) and to the right of the range constraint (R) are not acceptable.

The range production constraint only limits higher forest cover density levels, and, because snowpack water constraint increases with lower density levels, can not be considered limiting. However, as density levels decrease, increasing snowpack water content, the timber production constraint is approached. This constraint can not be lowered, at least if the stated minimum annual growth per acre is retained. To complicate matters, successively greater gains in snowpack water content per incremental change in forest cover density are realized as the timber constraint is approached.
Figure 11. Management Guideline Model Illustrating Possibilities for Increasing Snowpack Water Content at Peak Accumulation by Reducing Basal Area. Acceptable Possibilities Lie between the Timber (T) and Range (R) Production Constraints.
Management between the constraints is dependent, in part, on the values placed on water production relative to the values placed on timber production. If water is valued higher than timber, management re-direction toward the timber is made. The management position assumed with respect to the timber constraint will be determined by how much water values exceed timber values. If timber is valued higher than water, management re-direction away from the timber constraint is made. Again, the management position assumed will be determined by the value differential.

Ultimately, management must be evaluated in terms of the total benefits realized and the total costs borne within the economy as a whole. All forest-based products need to be considered. Management re-direction between the constraints will be justified only if the total benefits derived by the management system exceed the total costs of management implementation and maintenance.

It is assumed that a management system that maximizes snowpack water content on site provides the maximum potential for recoverable water derived from snow. The land manager will probably have little opportunity to affect runoff efficiency on a decision-making unit. However, he can insure that the maximum snowpack water content is available for conversion to recoverable water within the framework of multiple use management constraints and forest-based product benefits and costs.
Volume. Similar analytic procedures and subjective reasoning as described above are applied in developing a management guideline model involving forest cover volume. Solving the appropriate trade-off coefficient, $-0.812 \ln V$ (Table 15), in terms of incremental changes in volume allows corresponding gains in snowpack water content to be determined. As with the basal area development, timber and range production constraints may limit the flexibility in management possibilities, however.

The timber production constraint has been given as at least an annual growth of 20 cubic feet per acre. Assuming a growth percent of 1.7, as measured on the Campbell Blue and Beaver Creek study areas, the volume necessary to sustain minimum growth varies from 1,050 to 1,175 cubic feet per acre, depending on tree size and the intermingling of size classes.

A range constraint of a minimum production level of 50 pounds dry-weight of forage per acre has been specified. Conversion to basal area indicated densities in excess of 160 square feet per acre would restrict forage production to this minimum value. Translating square feet of basal area to cubic feet, using the intermixture of size classes measured on Campbell Blue and Beaver Creek, suggests that volumes in excess of 3,250 cubic feet per acre would restrict forage production to waste range.

When the skeletal model is combined with the timber and range constraints, the basic management guideline model is defined (Figure 12).
Figure 12. Management Guideline Model Illustrating Possibilities for Increasing Snowpack Water Content at Peak Accumulation by Reducing Volume (Cubic Feet). Acceptable Possibilities Lie between the Timber (T) and Range (R) Production Constraints.
Management to the left of the timber constraint (T) and to the right of the range constraint (R) is not acceptable. Only management possibilities between the two constraints is acceptable. Due to the competitive relationship between snowpack water content and volume, the range constraint can not be considered limiting. The timber constraint is limiting, however.

Again, it is assumed that the land manager will have little opportunity to affect runoff efficiency. Therefore, perhaps all that he can hope to accomplish is to maximize snowpack water content on site within multiple use management constraints, and with considerations given to benefits and costs.

Silviculturally, the techniques, benefits, and costs of thinning ponderosa pine overstory have been documented (Flora 1966, Gaines and Kotok 1954, Mowat 1953, Pearson 1950, Wikstram and Wellner 1961). This information, coupled with the management guidelines developed above, should facilitate the implementation of an effective operational multiple use management system designed to increase water yield within the framework of silvicultural requirements necessary to maintain timber production.

The problem of slash left in the woods following the thinning of forest cover needs consideration, both silviculturally (Hawley and Smith 1954) and from the standpoint snowpack dynamics (Hansen and Ffolliott
1968, Lejcher 1969). On the Campbell Blue study area, the basis for most of the output data used in this study, cutting of the timber overstory had taken place one year before snowpack measurements. Approximately two-fifths of the merchantable sawtimber was removed with this cutting. The resulting slash was left in place, with occasional lopping and scattering to facilitate the removal of commercial wood pieces. Consequently, the inventory-prediction data obtained on Campbell Blue are assumed representative of this form of slash disposal.

If future studies should show that the inventory-prediction equations and trade-off coefficients developed here are either incorrect or not appropriate for the decision-making units for which they are intended, similar methodologies as described above could still be applicable for the construction of management guidelines. Regardless of the value of the trade-off coefficient, if the basic relationship between snowpack water content and forest cover is competitive, as is commonly documented, a timber production constraint will probably limit management possibilities.

Economic Considerations

As a representation of the behavior of a physical and biological system, the management models developed above attempt to simulate a system before and after a management re-direction designed to increase water yield has occurred. Because the simulated changes in the system are intended for evaluations at the decision-making unit level, these
models could possibly be considered microeconometric models (Chappelle 1966). A microeconometric model is a statistical model, i.e., the relations are stated in terms of probability distributions, which operates at the level of the firm (decision-making unit). In contrast, a macroeconometric model is a statistical model that operates at the level of the economy as a whole.

Although microeconomic models may provide inputs into macroeconomic models, the basic decisions regarding the implementation of land management practices designed to increase water yield derived from snow can perhaps best be made within the framework of the former. Decisions made at the macro level may facilitate the development of overall policy, but these decisions could be insensitive or inflexible to local multiple use management constraints.

The application of theoretical economic analysis to solve multiple use management problems as formulated in microeconomic models has been used (Gregory 1955, Heady 1952, Hopkin 1956) in attempting to determine the resource combinations that maximize returns to the land in terms of revenue generated by different levels of production. However, these analyses have often been made without considering problems of alternative management design or the investment nature of choices (Black 1963, Miller 1969, Muhlenberg 1964).
The dual capital-product character of the timber resource, the long-term production cycle of timber, and the changing costs and values over time (Duerr 1960, Miller 1969) also limit the use of the basic joint-production model.

Additional difficulties encountered in applying economic theory include insufficient or incomplete knowledge of the physical and biological relationships involved, and not considering the full spectrum of benefits and costs external to the decision-making unit (Gould 1965, Herifindahl 1969, Miller 1969). All of these limitations need to be considered before theoretical economic analyses can be effectively applied in the development of efficient water yield improvement programs.

For some multiple use problems, a simple array of the estimated forest-based product responses to alternative management proposals, along with the direct benefits and costs, may be all that is required to describe a course of action on a decision-making unit (Hewlett and Douglass 1968, McConnen 1967, Worley 1966, Worley 1967). However, the problem becomes more complex in developing a multiple use program for a large area containing a variety of decision-making units (strata), each of which may react differently to the alternative management proposals. The alternative proposals, in turn, may have different direct benefits and costs within the decision-making unit complex. The problem now becomes one of designing the optimum group of management alternative.
Computer-oriented analytic techniques have been developed (Amidon 1966, Davis 1967, McConnen, Navon, Amidon 1965, Navon, 1967, Navon and McConnen 1967) to provide models by which the optimum mix of management alternatives can be determined for a variety of decision-making units. Hopefully, the inventory-prediction data and the management guidelines developed in this study can serve as decision-making inputs for these analytic techniques, or as sideboards to the interpretation and application of the results obtained.
CONCLUSIONS

Empirical inventory-prediction equations describing snowpack dynamics as functions of readily available or easily obtained inventory data can be developed for use in the ponderosa pine type in Arizona. These equations, which characterize specific snowpack conditions, include estimating parameters that index interception of precipitation inputs, obstruction of direct beam solar radiation, and re-radiation from trees onto the snowpack.

Expressions of forest cover density received primary consideration in the development of independent variables for inventory-prediction equation syntheses. Of these variables, snowpack dynamics were better related to basal area, bole area, volume, and height-index than to point density, sum of diameters, and number of trees. Additionally, potential direct beam solar radiation, elevation, and precipitation inputs were significant independent variables in many equations.

Forest-snow prediction techniques and management guidelines can be developed within the framework of the inventory-prediction equations. With the prediction techniques developed, the mean snowpack water content on a basin can be estimated, and the trade-off between snowpack water content and forest-site variables on a decision-making
unit can be defined. Management guidelines formulated outline management possibilities designed to maximize snowpack water content on site within limitations imposed by multiple use management constraints and forest-based product benefits and costs.

The basic objective of multiple use management is to manage the forest-based product mix for the most beneficial combination of present and future uses. The idea of maximizing the benefits from a given resource production base is not necessarily new, but it has become more important as competition for limited and interrelated products increases.

Multiple use management may be accomplished by any one of the following options, or by combinations of the three (Ridd 1965):

1. Concurrent and continuous use of the several forest-based products obtainable from a given decision-making unit.

2. Alternating or rotating the uses of the various forest-based products or product combinations on a unit.

3. Geographical separation of the uses or use combinations of the forest-based products so the multiple use is accomplished across a mosaic of units.

The inventory-prediction data, prediction techniques, and management guidelines developed in this study provide information useful in integrating forest-snow management systems within the multiple use concept as outlined by the above options. Primarily, the study output
permits evaluations of the concurrent and continuous use of forest-based products by considering the constraints necessary to insure multiple use production. However, the study output also provides guidelines for evaluating resource combinations when altered or rotated. These guidelines are based on descriptions of potential recoverable water yield production which approximate conditions that occur throughout the life-cycle (rotation) of a timber stand. If geographic separation of resources is specified, with either water or timber products not considered in the management of a decision-making unit, the study data will allow evaluation of the incidental production by these two products.

Resource-oriented multiple use research, as exemplified by this study, seeks to determine the interrelationships among forest-based products by describing how the management of one product affects the production of others (Bethune and Fortson 1969, McConnen 1967, Ridd 1965). Essentially, the rates of substitution among products and associated benefit-cost comparisons are considered (Black 1963, Gregory 1955, Hopkin 1956, Muhlenberg 1964, Worley 1966).

The information obtained from resource-oriented multiple use analysis is basic to the understanding of the inherent production capacities of the land. However, to accomplish effective and efficient multiple use land management, encompassing water-oriented objectives, resources must not only be related to each other but also to the needs and wants of
people (Kelso 1963, Ridd 1965, Tackle 1968). Only by examining the full spectrum of the physical, biological, economic, and social factors relating to resource development in a particular place can information of importance to the administration of a given decision-making unit be arranged, analyzed, and evaluated.
# Appendix

## S. C. S. Cooperative Snow Survey Plots

<table>
<thead>
<tr>
<th>Name</th>
<th>Sec</th>
<th>Twp</th>
<th>Rge</th>
<th>Elevation</th>
<th>River Basin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bear Wallow</td>
<td>6</td>
<td>12S</td>
<td>16E</td>
<td>8100</td>
<td>Gila</td>
</tr>
<tr>
<td>Beaver Head</td>
<td>13</td>
<td>4N</td>
<td>30E</td>
<td>8000</td>
<td>San Francisco</td>
</tr>
<tr>
<td>Canyon Creek</td>
<td>18</td>
<td>11N</td>
<td>15E</td>
<td>7500</td>
<td>Little Colorado</td>
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<tr>
<td>Chalender</td>
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<td>3E</td>
<td>7100</td>
<td>Verde</td>
</tr>
<tr>
<td>Copper Basin Divide</td>
<td>23</td>
<td>13N</td>
<td>3W</td>
<td>6720</td>
<td>Verde</td>
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<td>Forest Dale</td>
<td>2</td>
<td>9N</td>
<td>21E</td>
<td>6430</td>
<td>Salt</td>
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<td>Fort Valley</td>
<td>22</td>
<td>22N</td>
<td>6E</td>
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<td>11N</td>
<td>15E</td>
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<td>Salt</td>
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</tr>
<tr>
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<td>2W</td>
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