SNOW ACCUMULATION AND MELT UNDER VARIOUS DENSITIES OF PONDEROSA PINE IN ARIZONA

by

Terrence Richard Lejcher

A Thesis Submitted to the Faculty of the

DEPARTMENT OF WATERSHED MANAGEMENT

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

1969

STATEMENT BY AUTHOR

This thesis has been submitted in partial fulfillment of requirements for an advanced degree at The University of Arizona and is deposited in the University Library to be made available to borrowers under rules of the Library.

Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the major department or the Dean of the Graduate College when in his judgment the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

SIGNED: Terence Richard Lejcher

APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

David B. Thorud
DAVID B. THORUD
Assoc. Professor of Watershed
Management

February 2, 1969
Date

ACKNOWLEDGMENTS

The author wishes to express deep gratitude to Dr. David B. Thorud for the patience and assistance in the research and manuscript preparation for this thesis.

Special thanks are also extended to Dr. John L. Thames, Dr. Phil R. Ogden, Dr. Robert O. Kuehl, and Dr. Alan B. Humphrey for aid in the analysis of the data. Herbert S. Garn, Joan Stone, Robert Cunningham, Michael Jones, Keith Schubert, and Gilbert Schubert are thanked for invaluable assistance in data collection and compilation.

Most sincere appreciation is rendered my parents for encouragement in the pursuit of higher education and to the John L. Thames family who provided the warmest of friendships in a home away from home.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF ILLUSTRATIONS

ABSTRACT

Snow accumulation and melt patterns under several densities of ponderosa pine were analyzed using three statistical methods. Through the use of multiple linear regression, three prediction equations were developed. The most successful of the three equations predicted the melt rate of the snowpack using basal area and melt degree days as major variables. Path coefficient analysis was used to determine the relative importance of particular variables on snowmelt. Duncan's New Multiple Range test compared means of snowpack water equivalent in several stand densities during the melt phase.

It was concluded that different ponderosa pine stocking levels did not influence snow accumulation. However, snow did melt more rapidly in stands of low density than in stands of high density.

INTRODUCTION

Snow resources of north central Arizona are a vitally important source of water in the state. Reservoirs which retain snowmelt water in the Salt-Verde River basin provide critical supplies throughout the summer to the dry, fertile lowlands.

Since much of the annual snowfall in Arizona occurs in the ponderosa pine timber type found on the Mogollon Plateau, the influence of ponderosa pine management on snow accumulation and melt could be important. The average annual precipitation on the plateau is about 25 inches of which about 40 to 45 percent is snow. A primary goal of timber producers on the Mogollon Plateau is even-aged management. Timber management methods to induce maximum runoff are also a major current concern.

Timber clear-cutting practices apparently affect snow accumulation and melt rates, but the influence of different thinning levels on the snow has received minimal investigation, particularly in the ponderosa pine type of Arizona. It has been suggested that snow will accumulate to greater depths in the stands of low density than in those of high density, presumably because of decreased opportunity for vaporization of intercepted snow in low density stands. If low density stands have greater snow accumulation and melt rates, they may yield more runoff.

To evaluate this hypothesis, a stand of ponderosa pine previously thinned to several basal area levels was studied. This project was a cooperative study between The University of Arizona and the Rocky Mountain Forest and Range Experiment Station, which provided support.

LITERATURE REVIEW

Factors affecting snow accumulation and melt have been studied since about 1900, but most of the work dates from 1945. Recent studies concentrated on various types of strip cutting, block cutting, diameter limit cutting or other such methods giving the forest the "honeycombed" feature described by Church (1912). The influence of stand density on snow accumulation and melt has been studied but in most cases effects were confounded by the presence of several tree species and several age classes. Little research has been done on different stand densities of the same species, and only two such studies have been undertaken in Arizona. One aim of most cutting practices in the snow zones of other regions has been to delay snowmelt. In Arizona, it may be more beneficial to increase the rate of snowmelt, thereby reducing evaporation and transmission losses.

Jaenicke and Foerster (1915) were the first to study forest and snow relationships in Arizona. Their study was conducted close to this project location. Four years of record indicated no consistent relationship between snowfall in a forest park and snowfall in a forest. During the winter of 1912-13, which was a period of heavy snowfall, the forest park accumulated 7.98 inches of water while the forest accumulated 7.93 inches. Water equivalent differences were greater in winters of less snowfall. Snowmelt during the winter was more rapid in the forest than in the forest park because the average forest temperature was greater than the average forest park temperature. Pearson (1913) presented temperature data to support Jaenicke and Foerster (1915). However, during the rapid spring thaw, the melt rate in the forest park was much higher than in the forest, and the snow disappeared in the forest park 10 to 15 days sooner than in the forest.

Wilm and Collet (1940) found optimum conditions for snow accumulation and melt in heavily thinned forests rather than in large forest openings. However, on the Fraser Experimental Forest in Colorado, Goodell (1952) discovered that single tree thinning and crop tree thinning of lodgepole pine (basal areas of 36.2 and 43.3 square feet per acre, respectfully) increased the net snowpack water equivalent by about 1.5 inches or only 6.0 percent of the total annual precipitation. Although Goodell (1952) found no significant differences in accumulation between the two thinning conditions, Love (1953) indicated single tree thinning increased the water equivalent by 23.0 percent while crop tree thinning increased water equivalent by 16.8 percent in lodgepole pine. Berndt (1961) studied snow accumulation in mature ponderosa pine and Douglas-fir for two years and found a selectively cut area of 94 square feet per acre averaged 15 percent more snow than an uncut stand of 128 square feet per acre, while a commercially cut area of 43 square feet per acre averaged 51 percent more snow when compared to the same uncut stand.

In the Cascade-Sierra Nevada mountains in California, Anderson, Rice, and West (1958) found that snow accumulation increased as crown density, expressed as hemispherical cover, increased to 33 percent. As hemispherical cover increased beyond 33 percent, snow accumulation decreased. Anderson and Gleason (1960) published results indicating a young red fir stand (12,000 fbm/A.) accumulated 16.4 inches more snow water than an old dense stand (100,000 fbm/A.). An old open red fir stand (50,000 fbm/A.) accumulated 15.4 inches more snow water than the same old dense red fir stand. They found no consistent relationship between snowmelt and stand density. Similarly, Anderson (1960) suggested a forest of 20-50 percent crown density accumulates 4 percent more snow than a forest of 50-80 percent crown density and 20 percent more than a forest of 80-100 percent crown density. Intermediate cuttings of lodgepole pine, Engleman spruce and subalpine fir in Colorado increased snowpack accumulation and melt rates in proportion to the amount of cutting, according to Hoover (1960).

Wilm and Dunford (1948) conducted a sophisticated study of the relationships between snow and forest density in the Colorado lodgepole pine type. They discovered a roughly linear increase in water content of the snowpack as stand density decreased. With an uncut stand of 11,900 board feet per acre used as a control, stands of 6,000, 4,000, and 2,000 board feet per acre had greater snow accumulation by 11, 13, and 20 percent, respectively, for a 3-year period. The snowpack disappeared from all of the stands at about the same time. Kittredge (1953) also conducted an excellent study in the Sierra Nevada mountains. Using linear regression analysis, he gave the following results. For snowpacks with less than 3.0 inches of water content at maximum accumulation, a 10 percent increase in crown cover decreased snowpack water content by 0.5 inch. For seasons of heavier snowfall, there was a decrease of 1.6 inches of snowpack water content for each 10 percent increase in crown cover. These results were for seven years in cover types of ponderosa pine, red fir, white fir, Douglas-fir, and mixed conifers. Kittredge (1953) indicated that both mature ponderosa pine with 21 percent crown density and ponderosa reproduction with 79 percent crown density intercepted 15 percent of the incoming precipitation. Contrary to this, Connoughton (1935) indicated that mature ponderosa pine in Idaho intercepted 33.5 percent of the snowfall while immature ponderosa pine intercepted only 18.3 percent of the snowfall. However, he measured interception as the difference in water content of forested stands compared to open sites, which may be in considerable error due to snow trapping in the openings. Kittredge (1953) observed equal melt rates in mature ponderosa pine and ponderosa pine reproduction which supported Wilm and Dunford's (1948) finding of no significant relationship between snowmelt and crown density.

Ffolliott, Hansen, and Zander (1965) sampled snow in ponderosa pine stands of Arizona at five random points in each of four different basal area levels. The lowest even-aged basal area level (65 square feet per acre) accumulated the most snow, while the highest even-aged basal area level (115 square feet per acre) accumulated the least snow. However, both even-aged stands had higher melt rates than two uneven-aged stands. Anderson's (1956) results indicated that the melt rate in a dense forest of full shade was 53 percent of that in a large unshaded area. The forest of low density accumulated more snow and the snow melted much faster than in a forest of high density.

DESCRIPTION OF STUDY AREA AND WEATHER EVENTS

The study was conducted in Taylor Woods located on the Snow Bowl Road one mile north of U. S. Highway 66. The area is seven miles west of Flagstaff, Arizona, and one mile east of the Fort Valley Experimental Station. Elevation is 7350 feet.

Study Sites

Taylor Woods is an even-aged stand of ponderosa pine. Plots ranging from 0.50 acre to 1.25 acres with basal area levels from 0.0 to 97.5 square feet per acre were selected. Average tree heights ranged from 25 to 30 feet, and average diameters ranged from 5.1 inches to 7.5 inches. The distance between any two plots did not exceed 3300 feet. There were no elevation differences among the plots.

Weather Events

The average annual precipitation for the area was 22.6 inches with an average annual snowfall of 88.3 inches total depth for the period 1909 to 1957 as recorded by the U. S. Forest Service at Fort Valley. Average monthly water content of the snowpack for the period 1947 to 1964 ranged from 2.3 inches on February 1 to 1.2 inches on April 1, according to Enz (1964), at Fort Valley, Arizona.

An unusual snow storm occurred in the 1967-68 snow season. On December 12, 1967, at 2400, snow began to fall and did not cease falling, except for short intervals, until December 20, 1967. Ludlum (1968) reported the December 13 snowfall in Flagstaff as 26.8 inches followed by 15.5 inches on December 14. Snowfall continued until 2000 on December 15 and began again at 1200 on December 16, continuing to 0500 on December 17 and accumulating another 9.5 inches. After a 24-hour pause, a third snowfall began and lasted until 2300 on December 19, adding 29.9 inches to that already on the ground. The U. S. Weather Bureau at Flagstaff reported a total snow accumulation of 84 inches containing 7.62 inches of water. This storm produced the deepest accumulation on record for such a short period of time and accumulated 3 to 5 times more snow than the normal December precipitation for the Flagstaff area according to Enz (1968a).

Normally, winter storm systems approach the Mogollon Plateau from the southwest and generally place from 4 to 15 inches of snow on the ground. The storm system breaks up rapidly and cloud cover does not persist after precipitation has ceased. Sellers (1960) reported that winter clouds consist primarily of high cirrus and altocumulus clouds. However, the December 1967 storm was caused by a rare combination of an upper low pressure trough over the state with a surface low pressure system. Snowfall on December 13 through December 15 was the result of a surface low centered in eastern Arizona. This explains the unusual northerly direction from which the snowfall came. At this time an intense 500 mb upper low was in the process of formation. Centered over southern California, the low intensified during December 13 through December 16. It brought substantial amounts of moist air into northern Arizona which resulted in part of the heavy snowfall. The predominant flow of the upper air was from the south while the surface air flow was light. As the upper low moved to the east, a surface stationary front developed from a low pressure center in southeastern Oregon on December 18. The front pushed across northern Arizona on December 19, bringing the remaining snowfall to the Flagstaff area.

Measurement Periods

The storm described above was the only snow event of importance in the 1967-68 snow season. There were no significant changes in the water content of the snowpack in the Flagstaff area through January (Enz 1968b). Minor fluctuations in the water content of the snowpack in Taylor Woods from December 27, 1967, to January 30, 1968, were attributed to measurement error and possible evaporation and condensation processes in the snowpack. Also, a minor new snowfall of about 4 inches (0.75 inches of water content) was measured on January 30, 1968. The Soil Conservation Service reported that on February 1, 1968, the water equivalent of the snowpack was 267 percent of the 1948-62 average in the Flagstaff area (Enz 1968b).

Subsequent measurement in Taylor Woods after January 30, 1968, indicated significant decreases in the snowpack water content. The date of maximum accumulation was designated as January 30, 1968. The snowpack began to lose water sometime between January 30 and February 10, because there was enough heating to increase the density of the snowpack to about 0.35 gm-cm^{-3}, that is, the point where water losses are induced. Melt continued, with no measurable snowfall events, until an estimated date of March 5. Since temperatures were above normal and there was no significant precipitation during the melt period, the snowpack began to lose water 3 to 4 weeks earlier than the 1948-62 average for the Flagstaff area (Enz 1964). The last measurement of water content was February 25, 1968. On March 2, the small amount of remaining snow was measured to the nearest inch of depth and the water content was estimated. Thus, the melt period covered approximately 35 days.

METHODS AND PROCEDURES

Various stocking levels were represented by 16 selected plots in Taylor Woods. The location, size, and basal area of each plot measured is presented in Figure 1.

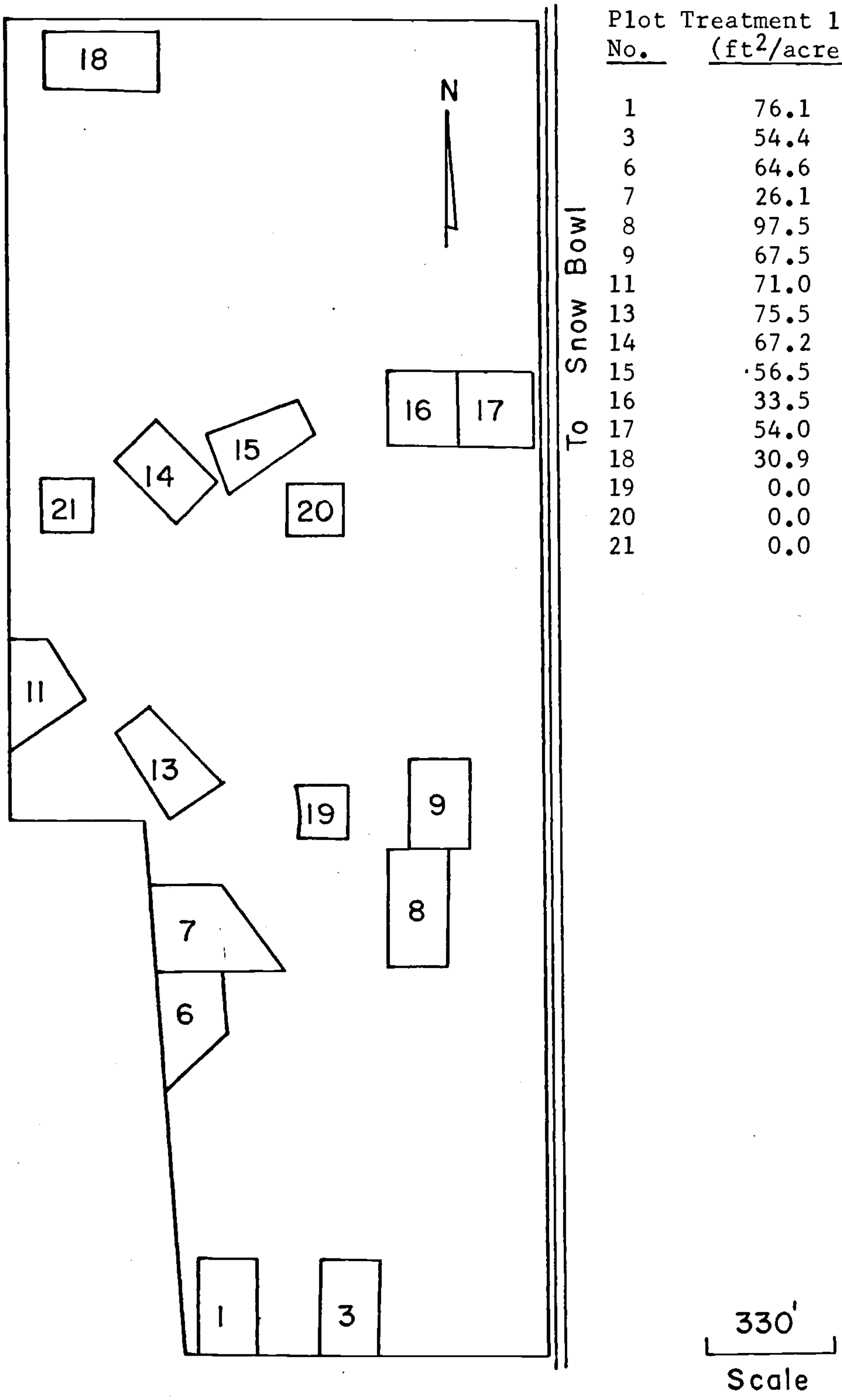
Plot Description and Sampling Locations

The study area is 88.6 acres in size and varies from 900 to 1230 feet wide east to west. It is 3300 feet long north to south.

An isolation strip 30 feet wide around each plot was not sampled. A strip 60 feet wide also was not sampled around plots on the windward side of the study area to the west (Figure 1). Since edge effects can influence both accumulation and melt (Anderson 1963; Ffolliott, Hansen, and Zander 1965; and Rothacher 1965), these zones were not measured in order to obtain a more representative estimate of stocking level influences on the snow regime.

Ten sampling points were located in each of the plots. Points were randomly selected from a 100-point grid layed over a map of each plot. A 5-foot steel rod, 0.25 inches in diameter, was placed at each sampling point. The rods were numbered and flagged. An area 4 feet to the north and 4 feet to the west of the steel rods was cleared of slash and used for sampling. The slash was removed to facilitate sampling and to minimize confounding effects of slash within plot treatments.

Hygrothermographs were installed on five plots to determine the intensity and duration of melting temperatures. The basal area levels



Plot No.	Treatment level (ft²/acre)	Size (acres)
1	76.1	1.00
3	54.4	1.00
6	64.6	1.10
7	26.1	1.25
8	97.5	1.00
9	67.5	0.75
11	71.0	0.75
13	75.5	0.75
14	67.2	0.75
15	56.5	0.75
16	33.5	0.75
17	54.0	0.75
18	30.9	1.00
19	0.0	0.50
20	0.0	0.50
21	0.0	0.50

Figure 1. Taylor Woods

included were 30.9, 56.5, 67.2, 67.5, and 97.5 square feet per acre. The hygrothermographs were precalibrated in a growth chamber. Maximum-minimum thermometers were installed in each instrument shelter for calibration purposes. Melt degree days (i.e., the sum of the average hourly degrees above 32°F divided by 24 hours) were calculated from temperature data.

Sampling Techniques and Instrumentation

The water content, snow depth, and snow density at each sampling point were determined with the Mt. Rose snow sampler. Work *et al.* (1965) reported that this snow sampler overestimates snowpack water equivalent by 7 percent in shallow snow of low density and by 10 to 12 percent in deep snow of high density. This error was probably consistent over the range of basal area levels where snowpack characteristics were determined. Therefore, the precision of the estimates *is* not affected by the inaccuracy of the snow sampler. These limitations were not considered of major importance in this study since relative differences rather than absolute values were the primary interest.

Two sampling crews measured snowpack characteristics at one half of the sampling points in each basal area level. This was done to reduce variation between basal area levels due to instrument error and human bias in reading the spring balance. Both snow depth and water equivalent were measured to the nearest 0.5 inch.

Snow samples were obtained in a consistent manner. The first sample was taken at the southeast corner of the sampling area at least 10 inches from the steel rod. At this distance, the stake did not influence the measured snow characteristics. As the snow season progressed, consecutive samples were taken in a westerly direction at least 6 inches from the previous sample. When the edge of each sampling area was reached (4 feet from the stake), the samples were taken 6 inches to the north of the first sample point and again continued in a westerly direction (Figure 2). The influence of sampling holes on the snow in the sampling area was not noticeable until the snow was only 2 to 3 inches deep (Figure 3).

Snow characteristics were measured on seven dates spaced at two to three week intervals during the accumulation period and at weekly intervals during the melt period. Each sampling day presented a different problem.

On December 27, 1967, seven days after the first snow storm, the first set of measurements was obtained. As the air temperature rose above freezing, the snow began to stick inside the snow sampler. This prevented obtaining a snow core of sufficient length. To overcome this problem, a push rod with a cloth tied to the end was run through the sampling tube before each measurement was made. This cleared the sampling tube and reduced the difficulty. The same procedure was followed on January 7, 1968, the next sampling date. On January 30, 1968, the inside of the snow tubes were waxed and no problems were encountered. On this date, approximately 4 inches of new snow was present. The fresh snow was measured to the interface of the old and new snow, which was easily identified by the crusted surface of the old snow. Samples were also taken of the entire snowpack adjacent to the fresh

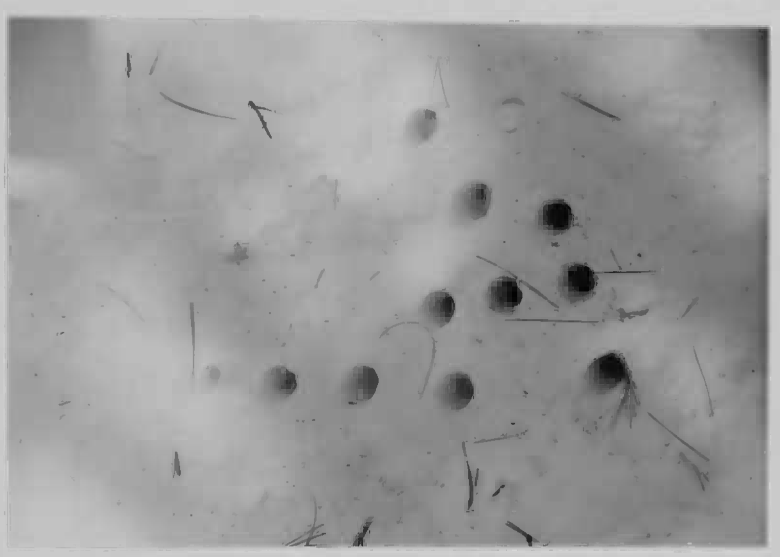


Figure 2. Snow sampling to the west and to the north of location stake.

Figure 3. Influence of previous snow sampling points on snow in plot.

snow sample location. The older snow had a crystalline structure and was comparatively wet. The average density of the entire snowpack ranged from 0.31 to 0.32 gm-cm^{-3}. Since the soil surface appeared nearly saturated on this date, it was decided the melt period was about to begin. January 30, 1968, was designated as the date of maximum accumulation (Figure 4).

February 10, 1968, was the first date of measurement during the melt period. A very light rain fell on February 9, which probably increased the water equivalent of the snowpack. Snow adjacent to tree trunks began to show accelerated melt on this date. On February 18, the next measurement day, effects of slash on melt became obvious (Figure 5). Some measurements in plots of 0.0 basal area indicated that the isolation strip of 30 feet was not wide enough. Sampling points on the south side of these plots, where shaded from the north side of the adjacent plots, had 2 to 3 inches more water than sampling points elsewhere on the plot. Needles and dust imbedded in snow surface were responsible for increased melt at some locations (Figure 6).

Because the snow was wet, it was difficult to keep the entire core in the snow sampler while withdrawing the tube. About 0.5 to 1.0 inch of new snow, which had fallen since the preceding measurement period, was not measurable. The last measurements with the snow tube were made without difficulty on February 25. On March 2, snow depth was measured at each sampling point where snow still remained. An estimated density of 0.43 gm-cm^{-3} was applied to all of the sampling

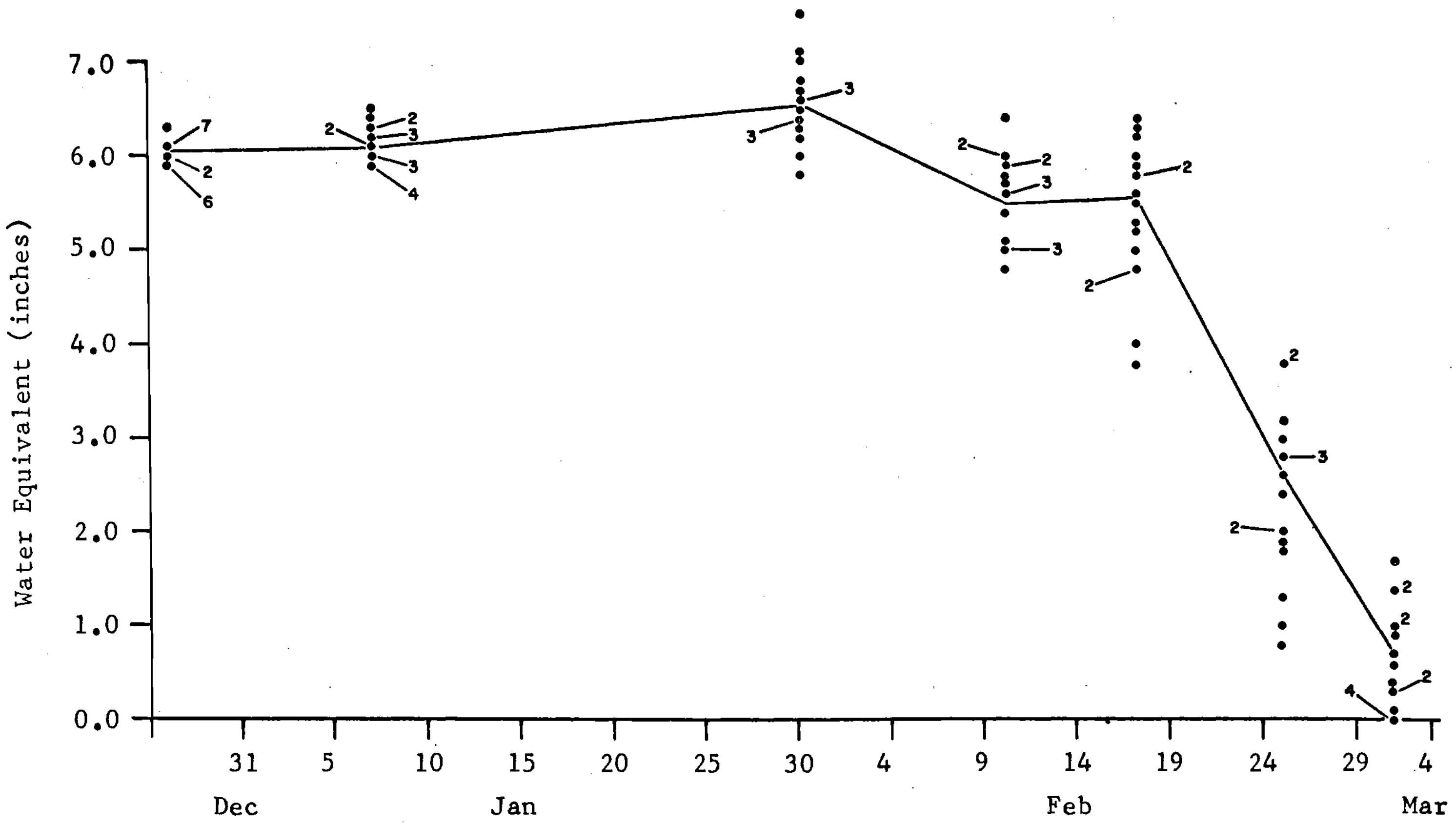


Figure 4. Average plot snow water content and variation in Taylor Woods 1967-68.

Figure 5. Slash influence on snowmelt.

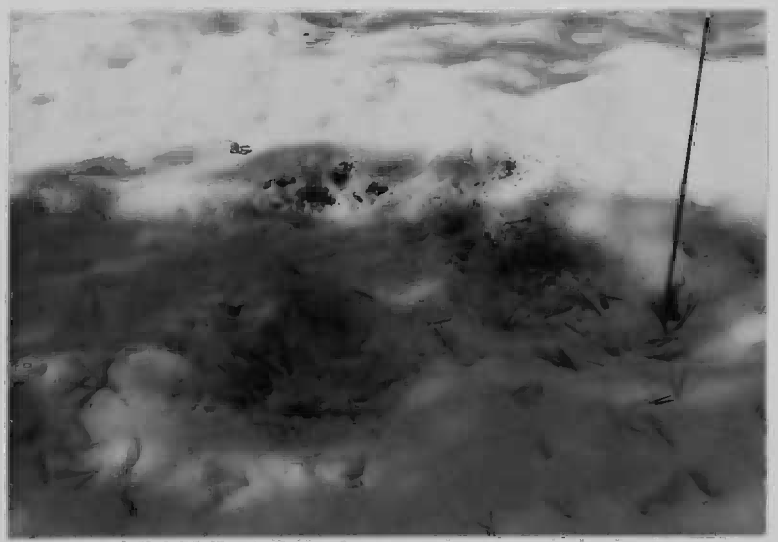


Figure 6. Dust, needle, and soil particle influence on snowmelt.

points to determine water equivalent. This density estimate was based on data from the preceding measurement period and the density of snow patches in the Flagstaff area on March 23, 1968.

ANALYSIS

Three statistical techniques were used in the analysis. Multiple linear regression on analysis was used to estimate the magnitude of a particular variable. Path coefficient analysis was used to determine relative effects of measured variables. Duncan's New Multiple Range Test was used to test mean water equivalents in different basal area levels. The accumulation period of December 27, 1967, to January 30, 1968, was analyzed separately from the melt period of January 31, 1968, to about March 5.

Stepwise Multiple Linear Regression

A stepwise multiple linear regression was used for both periods to estimate basal area and snowmelt parameters. Computations were made with the IBM 1600 computer at The University of Arizona. With this regression technique, a number of variables were selected in the order of their best fit to a model. In this analysis, if two X variables are highly correlated with the Y variable being predicted, the most highly correlated X variable is entered first in the model. The relative importance of the second X variable is masked by the first since correlation exists between any two X variables. Each successive variable entered into the model increases the coefficient of determination (R^2). The coefficient of determination is the percent of variation in the Y variable that is accounted for by the X variables in the proposed model. To obtain this percentage, the sum of squares of deviation due to regression in the analysis is divided by the total sum of squares, or:

$$R^2 = \frac{\sum b_i x_i y}{y^2} \tag{1}$$

In all cases, the hypothesis being tested is: $H_o: B_1 = B_2 = \ldots B_n = 0$, where B is the regression coefficient of each X variable. Partial regression coefficients were obtained by holding each preceding variable constant as the new variable was added to the model. The new variable was then held constant and compared to the variables previously entered. Thus, the rate of change of the predicted Y variable was measured per unit of change of the X variable.

Several models were tested using the multiple linear regression technique. For the accumulation phase, the model used to predict basal area for maximum snow accumulation was:

$$Y = B_0 + B_1X_1 + B_2X_2 + B_3X_3$$

where:

Y = basal area, in square feet per acre;
X_1 = snow depth, in inches;
X_2 = water equivalent, in inches;
X_3 = snow density, in gm-cm^{-3}.

Two models were used for the snowmelt phase. To determine the optimum basal area level for most rapid melt, the following model was used.

$$Y = B_0 + B_1X_1 + B_2X_2 + B_3X_3 + B_4X_4 + B_5X_5 + B_6X_6 \qquad (3)$$

where:

Y = basal area in square feet per acre;

X_1 = accumulated melt degree days between measurement periods;

X_2 = snow density, in gm-cm^{-3}, at the end of the measurement period;

X_3 = water equivalent lost, in inches, between measurement periods;

X_4 = (accumulated melt degree days)^2 between measurement periods;

X_5 = (snow density)^2, in gm-cm^{-3}, at the end of the measurement period;

X_6 = (water equivalent lost)^2, in inches, between measurement periods.

The second model used for the melt phase predicted water equivalent losses under different basal area levels as follows:

$$Y = B_0 + B_1X_1 + B_2X_2 + B_3X_3 + B_4X_4 + B_5X_5 \qquad (4)$$

where:

Y = water equivalent lost, in inches, between measurement periods;

X_1 = accumulated melt degree days between measurement periods;

X_2 = basal area, in square feet per acre;

X_3 = (accumulated melt degree days)^2 between measurement periods;

X_4 = (basal area)^2 in square feet per acre;

X_5 = accumulated melt degree days between measurement periods x basal area in square feet per acre.

During the accumulation phase, the only significant model tested was for the first measurement period immediately following the storm of December 12 through December 19, 1967. During the melt phase, the model to predict the optimum basal area level for the maximum melt rate and the model to predict maximum water equivalent lost were both tested for each of the four measurement periods.

Path Coefficient Analysis

Path coefficient analysis is a statistical technique which describes the portion of the total variation in a model accounted for by each variable. It can be used to determine the relative importance of variables analyzed with the stepwise multiple linear regression technique.

Path coefficient analysis is a special type of multivariate analysis. It deals with linearly related variables in a closed system. According to Li (1956), a closed system is one where ". . . each variable in the system is either a linear combination of some other variables in the system or is one of the basic factors, which may be correlated with or independent of other basic factors in the system." Nonlinear data may be transformed for this method of analysis. Path coefficient analysis is a cause and effect analysis with the measured variables being the causes and the predicted variable being the effect. The hypothesis tested is one of causal relationships among correlated variables. This technique overcomes the problem with stepwise multiple linear regression in which the importance of each variable is masked by the other variables.

The standard partial regression coefficient, or b'_x, is calculated for each X variable. This procedure standardizes the variance of each X variable, so all the X variables can be individually examined as to their effect on the predicted Y variable. The standard partial regression coefficients, or direct effects (D.E.), are calculated by the following formula, according to Li (1956):

$$\text{D.E.} = \frac{B_x \sigma_x}{\sigma_y} = b'_x \tag{5}$$

where:

D.E. = direct effect of X on Y or standard partial regression coefficient;

B_x = partial regression coefficient of X plotted against Y with all other variables held constant;

σ_x = standard deviation of the X variable with all other variables omitted;

σ_y = standard deviation of the Y variable with all other variables omitted;

b'_x = standard partial regression coefficient.

The cause and effect relationship is indicated in Figure 7 with a single headed arrow representing direct effects due to each variable.

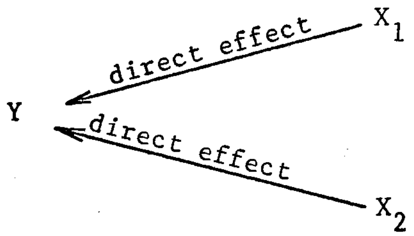


Figure 7. Diagram of Path Coefficient Analysis.

Duncan's New Multiple Range Test

Means of water equivalents in different basal area levels during the melt period were tested by Duncan's New Multiple Range Test. This test requires an unbiased estimate of the sampling variance. The test is advantageous in that it safeguards against the Type I error, where a true hypothesis is mistakenly rejected. The smaller the probability of the Type I error, the greater the power of the test, or the probability of rejecting a false hypothesis when the hypothesis is false.

The alpha level selected for this test was 0.10. The hypothesis tested was H_o: $u_1 = u_2 = . . . u_n$, where u is defined as the average water equivalent under each particular basal area level. Because variances of the water equivalents were heterogeneous, as determined by Hartley's maximum-F test, an adjustment in the degrees of freedom used in the Duncan's test was made.

Calculations were made as follows:

$$s_{\bar{x}} = \sqrt{\frac{s^2}{n}} \qquad (6)$$

where

$s_{\bar{x}}$ = standard error of the mean water equivalents;

s^2 = pooled variance of water equivalents of all plots;

n = number of samples per plot.

Then:

$$s_{\bar{x}} \times \text{NMRT} = \text{Significant Studentized Range at } \lambda = 0.10 \qquad (7)$$

The water equivalents were listed from high to low. If the difference between water equivalents did not exceed the Significant Studentized Range value for the number of means being compared, the mean water equivalents were not significantly different. By associating the proper basal area levels with their respective water equivalents, the influence of different stocking levels on water equivalent during the melt period was determined. This analysis was used to group basal area levels that had equivalent effects on snowmelt.

Missing Data and Assumptions

The multiple linear regression models did not fit all the assumptions of multiple linear regression analysis. All of the variables were multivariate; thus no variables were classified as dependent or independent. The normal multiple regression model assumes that the independent variables are measured without error. Since what may be called independent variables in this analysis were actually samples of the variable, they were in error.

Snow characteristics, used to predict optimum basal area levels, were only sampled. The averages of these samples were applied to respective basal area levels. The averages undoubtedly were not without error and thus did not represent true population parameters. Basal area measurements were probably in error, although every tree on each plot was measured.

Only five hygrothermographs were used to determine melt degree days. It was assumed that the melt degree days would not vary significantly within ± 5.0 square feet of the basal area where temperature was measured. Thus, melt degree days cannot be strictly classified as an independent variable.

Data from some plots were omitted from the analysis for the melt period. Two plots were located near the road leading to the Snow Bowl ski area. The road received heavy use and dried out during the melt period. Dust from the road settled on these plots and greatly increased melt rates. Thus, plot 17 (54.0 square feet per acre) was omitted after January 30, 1968. Plot 16 (33.5 square feet per acre) was omitted after February 18, 1968. Plot 9 (67.5 square feet per acre) had four sampling points located in a 60-foot diameter opening in the canopy. These points were not representative of that basal area level and were omitted from the analysis for both accumulation and melt phases.

Five days of temperature data were lost due to a malfunctioning hygrothermograph in the 56.5 square feet per acre stocking level. Using a linear regression coefficient calculated with temperature data from the plot with the missing data and the next most similar plot, the missing temperature data was estimated by regression.

RESULTS AND DISCUSSION

The results of this study will be presented for the accumulation phase of December 27, 1967, through January 30, 1968, and the melt phase from January 31, 1968, through March 2, 1968. Water content, density, and snow depth data are presented in Tables 1, 2, and 3. Figures in the tables are plot averages for each measurement date. Table 1 shows little difference in snowpack water content under the range of basal area levels for the first measurement period of December 27, 1967, and little difference for the 4-inch snowfall measured on January 30, 1968. After February 18, 1968, the snowpack melted rapidly (Figure 4). Snowpack density increased at a greater rate in the basal area levels below 50.0 square feet per acre (Table 2), and these plots lost meltwater more rapidly than stands of higher stocking.

Accumulation Phase

A relationship between water equivalent and basal area was the first to be explored. Simple linear regression coefficients of water equivalent versus basal area were calculated. The hypothesis tested was H_o: B=0. The results (Table 4) show the hypothesis of no slope was accepted in all cases at $\lambda = 0.10$. The coefficient of determination was very low and indicated an unsatisfactory relationship between basal area and water equivalent.

Several multiple linear regression models were attempted to explain the relationship between basal area levels and snow

TABLE 1

AVERAGE PLOT SNOWPACK WATER CONTENT IN INCHES

Plot No.	Basal Area	Total Snow 12-27-67	Total Snow 1-7-68	New Snow 1-30-68	Total Snow 1-30-68	Total Snow 2-10-68	Total Snow 2-18-68	Total Snow 2-25-68	Total Snow 3-2-68
19	0.0	5.9	6.1	0.65	6.6	5.9	5.5	1.3	0.0
20	0.0	6.1	6.0	0.90	7.1	6.0	6.2	1.8	0.6
21	0.0	6.1	6.5	0.60	6.2	6.4	6.0	2.4	0.1
7	26.1	6.3	6.4	0.80	6.8	6.1	5.8	2.8	0.3
18	30.9	6.1	5.9	0.65	6.5	4.8	5.2	1.9	0.0
16	33.5	5.9	5.9	0.80	6.0	5.0	4.8	1.0	0.0
17	54.0	6.1	6.3	0.55	5.8	5.0	3.8	0.8	0.0
3	54.4	6.1	6.2	0.60	7.0	6.0	5.8	3.0	1.4
15	56.5	5.9	5.9	0.70	6.6	5.6	5.3	2.0	0.4
6	64.6	6.1	6.1	0.65	6.4	5.6	5.9	2.8	1.0
14	67.2	5.9	6.0	0.65	6.4	5.0	4.8	0.0	0.3
9	67.5	5.9	5.9	0.60	6.3	5.8	4.0	2.8	0.9
11	71.0	6.0	6.3	0.85	7.5	5.9	6.4	3.8	1.4
13	75.5	6.0	6.0	0.65	6.6	5.7	5.6	3.2	1.0
1	76.1	5.9	6.2	0.70	6.7	5.6	6.3	3.8	1.7
8	97.5	6.1	6.2	0.60	6.4	5.4	5.0	2.6	0.7

TABLE 2

AVERAGE PLOT SNOWPACK DENSITY IN $gm\text{-}cm^{-3}$

Plot No.	Basal Area	Total Snow 12-27-67	Total Snow 1-7-68	New Snow 1-30-68	Total Snow 1-30-68	Total Snow 2-10-68	Total Snow 2-18-68	Total Snow 2-25-68	Total Snow 3-2-68
19	0.0	0.23	0.26	0.15	0.33	0.36	0.40	0.36	0.43
20	0.0	0.23	0.25	0.22	0.33	0.36	0.40	0.39	0.43
21	0.0	0.22	0.27	0.14	0.32	0.38	0.41	0.40	0.43
7	26.1	0.26	0.28	0.18	0.33	0.37	0.38	0.42	0.43
18	30.9	0.22	0.27	0.16	0.33	0.32	0.35	0.40	0.43
16	33.5	0.24	0.26	0.21	0.34	0.39	0.40	0.39	0.43
17	54.0	0.24	0.29	0.18	0.35	0.41	0.41	0.37	0.43
3	54.4	0.23	0.28	0.18	0.32	0.33	0.35	0.39	0.43
15	56.5	0.23	0.26	0.21	0.32	0.34	0.37	0.39	0.43
6	64.6	0.24	0.27	0.15	0.31	0.32	0.36	0.38	0.43
14	67.2	0.24	0.27	0.18	0.33	0.35	0.36	0.42	0.43
9	67.5	0.24	0.28	0.17	0.32	0.33	0.35	0.41	0.43
11	71.0	0.23	0.28	0.21	0.32	0.30	0.34	0.38	0.43
13	75.5	0.24	0.27	0.17	0.30	0.31	0.34	0.38	0.43
1	76.1	0.23	0.28	0.16	0.32	0.31	0.37	0.40	0.43
8	97.5	0.24	0.27	0.16	0.32	0.33	0.34	0.34	0.43

TABLE 3

AVERAGE PLOT SNOWPACK DEPTH IN INCHES

Plot No.	Basal Area	Total Snow 12-27-67	Total Snow 1-7-68	New Snow 1-30-68	Total Snow 1-30-68	Total Snow 2-10-68	Total Snow 2-18-68	Total Snow 2-25-68	Total Snow 3-2-68
19	0.0	26.6	23.6	4.3	20.6	16.2	13.6	3.6	0.0
20	0.0	26.7	23.8	4.2	21.5	17.1	15.4	4.6	1.4
21	0.0	27.9	23.8	4.4	18.9	16.9	14.6	5.8	0.3
7	26.1	25.7	23.0	4.4	20.4	16.8	15.5	6.8	0.6
18	30.9	26.2	22.5	4.1	19.8	14.8	13.2	4.8	0.1
16	33.5	26.2	22.4	3.9	17.8	13.0	12.1	2.7	0.1
17	54.0	25.2	22.1	3.0	16.4	12.2	9.2	2.2	0.0
3	54.4	25.8	22.7	3.4	22.2	18.9	16.6	7.8	3.7
15	56.5	25.2	22.2	3.3	20.9	16.6	14.4	4.9	1.1
6	64.6	25.4	22.8	4.2	21.0	18.0	16.1	7.6	2.2
14	67.2	24.8	21.8	3.6	19.3	14.4	13.2	4.8	0.7
9	67.5	25.0	21.5	3.6	18.2	14.0	11.0	4.1	1.2
11	71.0	25.6	22.4	4.5	23.6	19.8	18.8	9.8	3.8
13	75.5	24.9	22.3	3.8	22.0	18.6	16.1	8.4	2.9
1	76.1	25.8	22.6	4.2	21.6	18.8	17.2	17.5	4.2
8	97.5	25.8	22.6	3.8	19.8	16.2	14.6	9.4	1.8

TABLE 4

SIMPLE LINEAR REGRESSION RESULTS OF WATER EQUIVALENT VERSUS BASAL AREA

Date	Regression Coefficient	SSR	SSE	S_b	H_o:	T_{cal}	T_{tab}	Conclusion at $\lambda = 0.10$	R^2
12-27-67 total snow	0.19765	1.41145×10^2	3.60356×10^5	9.99	B=0	1.978×10^{-2}	1.771	Accept	3.9×10^{-4}
1- 7-68 total snow	0.75961	4.4044×10^1	7.49295×10^4	31.32	B=0	2.425×10^{-2}	1.771	Accept	5.8×10^{-4}
1-30-68 new snow	-2.66362	3.07443×10^2	7.45911×10^4	414.80	B=0	6.421×10^{-3}	1.771	Accept	8.3×10^{-2}
1-30-68 total snow	4.10273	4.35375×10^3	7.06198×10^4	16.52	B=0	2.484×10^{-1}	1.771	Accept	5.8×10^{-2}

characteristics. The most successful model predicted the basal area having maximum snow accumulation using snow depth, water equivalent, and snow density as variables. Results of the statistical analysis (Table 5) were used to determine the following prediction equation:

$$\text{B.A.} = -38.81 + 2.77\ \text{S.D.} + 652.40\ \text{Den.} - 25.27\ \text{W.C.} \qquad (8)$$

where:

B.A. = basal area in square feet per acre;
S.D. = snow depth in inches;
Den. = snow density in gm-cm^{-3};
W.C. = water content in inches.

With the inclusion of the third variable in the analysis, the model accounts for over 80 percent of the variation.

This model was statistically significant for only the first measurement period. Snow depth, varying from 24.8 to 27.9 inches, was the most important variable and it accounted for 76 percent of the variation in the model (Table 5). Water equivalent of the snowpack, the variable of most interest, was least important in the stepwise multiple linear regression analysis. Because water equivalent varied only 0.4 inch over a range from 0.00 to 97.5 square feet per acre of basal area on the first measurement date, basal area had no influence on the water equivalent of the snowpack. Since the Mt. Rose snow sampler measures water equivalent accurately only to the nearest 0.5 inch, instrument error is enough to account for this variation.

TABLE 5

STEPWISE MULTIPLE REGRESSION ANALYSIS PREDICTING BASAL AREA FOR MAXIMUM SNOW ACCUMULATION DECEMBER 27, 1967

Step	Term Entering	Partial Regression Coefficient	Standard Error of Coefficient	Y Intercept	Standard Error of Y	Coefficient of Determination	F Ratio
1	Snow Depth	2.150720	-0.098999	-22.027	24.108	0.7613	472.42*
2	Snow Depth	2.160615	-0.099475	-24.814	24.109	0.7629	236.58*
	Density	10.15651	10.23157	"	"	"	"
3	Snow Depth	2.768726	0.138414	-38.814	21.820	0.8071	203.70*
	Density	652.4037	111.4196	"	"	"	"
	Water Content	-25.26554	4.368002	"	"	"	"

* Indicates significance at 1% level.

Interception vaporization losses appear negligible for the snowfall measured on December 27, 1967. Satterlund and Haupt (1967) present autocatakinetic growth curves for snow interception in coniferous species indicating a point of maximum snow accumulation. Following their reasoning, it is probable that the forest canopy reached a point of maximum snow accumulation many times during this heavy snowfall. Mass transport processes of snow, as described by Miller (1966), undoubtedly relieved the tree crowns of excessive snow loads. Wind erosion and snow loads on the crown, exceeding the point of maximum accumulation, probably combined to cause snow to slide from the crowns during the storm. The forest canopy was holding very little snow at the time of measurement. Air temperatures above 32°F and considerable observed wind activity may have facilitated the mass transport processes after the storm.

Possibly the above model (8) was statistically significant for snow depth immediately following the storm because of both interception and mass transport processes. Continual release of snow from tree crowns may have slightly compacted the snowpack in dense stands. Stands of low density were not subjected to the same degree of compaction and consequently had greater snow depth. Since water equivalents in all basal area levels were not significantly different while snow depths were, most of the intercepted snow apparently fell directly below the forest canopy. If snow is removed from tree crowns in this manner for this area, variations in basal area levels may not significantly affect the snowpack water content during storms. Thus, there may be no optimum stand density for maximum snow accumulation.

The remaining two measurement periods of the accumulation phase were also analyzed by the multiple linear regression technique. The amount of variation accounted for on both dates was small and snow depth no longer remained the most important variable (Table 6).

TABLE 6

COEFFICIENTS OF DETERMINATION FOR EQUATION 2

Variable	Date			
	12-27-67 Total Snow	1-7-68 Total Snow	1-30-68 Total Snow	1-30-68 4" New Snow
Depth	0.7614	0.0498	0.1019	0.0679
Density	0.7629	0.1095	0.0836	0.0825
Water Content	0.8071	0.0933	0.1223	0.0684

These results may be due to rapid settling of the snowpack which could eliminate snow depth differences between various basal area levels.

The model was significant only for the immediate poststorm measurement period. It seems reasonable to propose that determination of snow depth by aerial reconnaissance immediately following a storm is usually uniform, a few density measurements could perhaps be combined with depth measurements from the entire watershed to determine the water equivalent.

Melt Phase

Accelerated snowmelt in Taylor Woods did not begin until the week of February 18, 1968 (Figure 4). However, on January 30, 1968, snow sampling cores revealed that the bottom of the snowpack was crystalline and that the pores appeared to be filled with water. The snowpack began to lose some liquid water at this time.

Several factors are responsible for the slow loss of water followed by a marked rapid loss. Density of the snowpack is one critical factor. On February 18, 1968, the average snowpack density in Taylor Woods was 0.37 gm-cm^{-3}. It seems that a critical threshold density of about 0.36 to 0.38 gm-cm^{-3} must be attained in the Flagstaff area before the snowpack loses water rapidly. Gravity forces probably become predominant when the bottom of the snowpack is saturated resulting in a rapid loss of water. It should be noted that a light rain fell in the area on February 9 and 10, 1968, and the remains of a light snow were visible on February 18, 1968. How these events affected water equivalent and snow density are not known, but estimated melt rates may have been confounded. Saturated soil beneath the snowpack after February 10, 1968, indicated that melt rates were greater than soil infiltration rates.

An equation to predict the basal area level with the most rapid melt rate was developed through multiple linear regression analysis. The equation is:

$$\begin{aligned} \text{B.A.} = \ & 18.21 + 5.21 \text{ M.D.D.} - 0.15 \text{ (M.D.D.)}^2 \\ & + 3.31 \text{ (M.D.D.} \times \text{M.R.)} - 75.68 \text{ M.R.} \end{aligned} \tag{9}$$

where:

B.A. = basal area in square feet per acre;

M.D.D. = melt degree days (i.e., the sum of the average hourly degrees above 32°F divided by 24 hours);

M.R. = loss of water equivalent between measurement periods or melt in inches.

The results of this model (Equation 3) when applied to each of the four melt measurement periods are summarized in Appendix B, Tables 1B through 4B. Melt degree days and loss of water equivalent, or melt rate, are the two most important variables in this equation. Snow density adds very little to the coefficient of determination. It is of interest to note that the partial regression coefficient for melt rate is negative for the period of most rapid melt. This indicates that the highest melt rate will be found in the lowest basal area level. Because the coefficient of determination is high (above 0.80) for all four measurement days, the model applied was assumed to be suitable for prediction purposes during the entire melt phase.

Perhaps the more important equation is the melt prediction equation, as follows:

$$\begin{aligned} \text{S.M.} &= 4.76 - 0.12\ \text{B.A.} + 0.007\ (\text{B.A.})^2 \\ &\quad + 0.006\ (\text{B.A.} \times \text{M.D.D.}) \end{aligned} \tag{10}$$

where:

S.M. = water equivalent lost between measurement periods or snow melt in inches;

B.A. = basal area in square feet per acre;

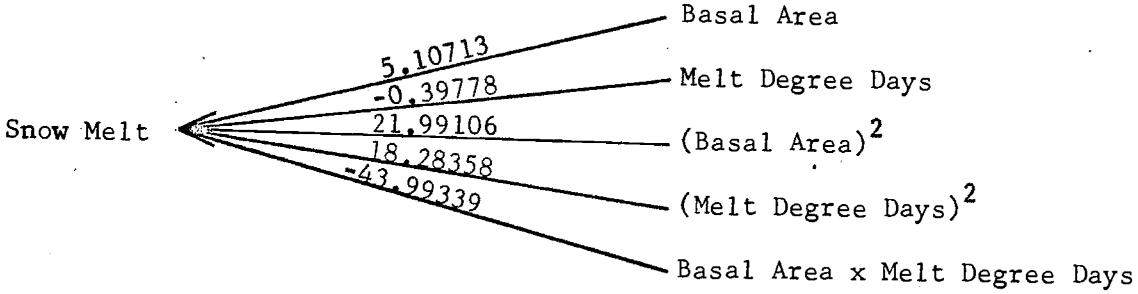
M.D.D. = melt degree days.

The coefficients of this equation are those determined for the week of most rapid melt at which time the model accounts for 90 percent of the snowmelt variation. The coefficient of determination is less earlier in the melt period, but increases from 0.47 to 0.92 as the melt rate increases (Appendix B, Tables 5B through 8B). For the first two measurement periods the F-ratio is significant for all intermediate steps, but the percent of variation in snowmelt accounted for by the total model is not considered sufficient for prediction purposes. Basal area and melt degree days are not as important determinants of early melt as they are of late melt. There is no consistent relationship between any partial regression coefficient and snowmelt.

Path coefficient analysis was used to determine the relative importance of individual variables in the snowmelt model. The results are presented in illustrated form (Figures 8 and 9). Each number above the arrow is the calculated direct effect (Equation 5). The magnitude of the interaction variable indicates that of all variables, it is most significantly related to snowmelt. The simple correlation coefficients for periods of snowmelt, however, indicate a negative correlation between the interaction variable and snowmelt (Table 7). Melt degree days squared is the second most important variable for the last measurement date. There is also a negative simple correlation between the remaining variables and snowmelt, except for the week of February 10, 1968, when there was a net gain of snowpack water.

Basal area was found to be an important determinant of air temperature indexed by melt degree days. The interaction between these

FEBRUARY 10, 1968



FEBRUARY 18, 1968

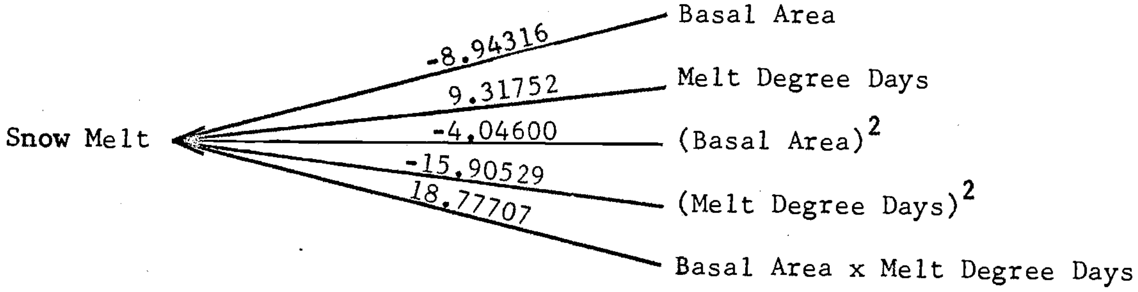
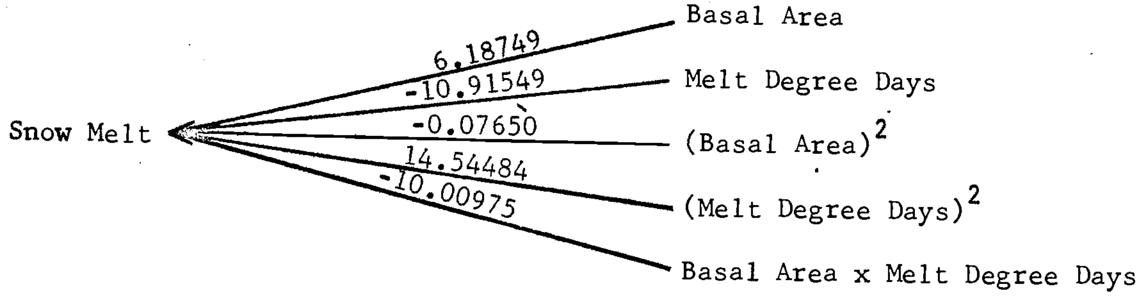


Figure 8. Path coefficient analysis for factors influencing snow melt. (February 10 and February 18, 1968)

FEBRUARY 25, 1968



MARCH 2, 1968

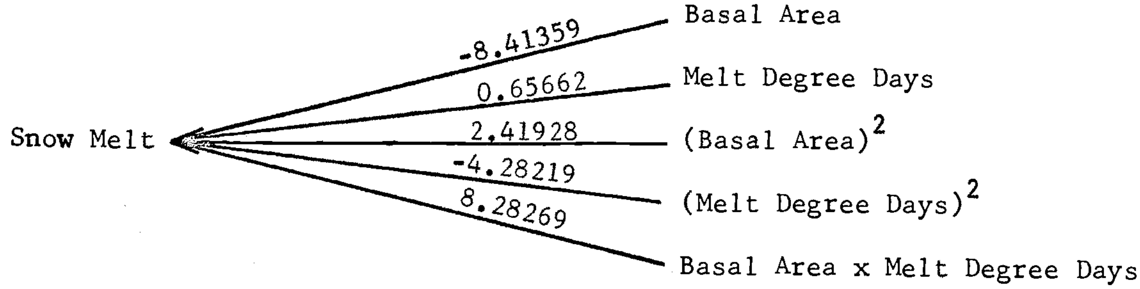


Figure 9. Path coefficient analysis for factors influencing snow melt. (February 25 and March 2, 1968)

TABLE 7

CORRELATION COEFFICIENTS IN PATH COEFFICIENT ANALYSIS

Variable	Date			
	2-10-68	2-18-68	2-25-68	3-2-68
Basal Area vs. Snowmelt	-0.192	0.139	-0.747	-0.394
Melt Degree Days vs. Snowmelt	-0.283	0.150	-0.439	-0.370
$(\text{Basal Area})^2$ vs. Snowmelt	-0.164	0.168	-0.760	-0.243
$(\text{Melt Degree Days})^2$ vs. Snowmelt	-0.276	0.153	-0.414	-0.282
Basal Area x Melt Degree Days vs. Snowmelt	-0.228	0.168	-0.655	-0.334

two variables and the effect on snowmelt is presented in Figure 10. The curves on the left side of the figure represent basal areas of 26.1 and 30.9 square feet per acre. The curves on the right represent basal area levels of greater than 50.0 square feet per acre. Cumulative melt degree days and cumulative snowmelt were calculated from the beginning of the melt period until the snowpack disappeared (Table 8). Figure 10 indicates that fewer melt degree days are required in lower stand densities than in higher stand densities to melt equivalent amounts of snow. However, Figure 10 also shows that fewer melt degree days were available to melt snow in the stands of low density.

These results imply that more sensible energy was available to melt snow in high stocking levels. Much of the total energy available in the dense stands was probably used to heat the forest canopy. This dense canopy may then have provided more longwave radiation to the snowpack to be utilized in the melt process than was provided in low density stands. The low stocking levels probably also had a greater loss of longwave radiation to the atmosphere than high stocking levels. For these reasons, total cumulative melt degree days were highest in the dense stands.

The snowpack under low density stands disappeared 2 to 3 days earlier than under high density stands. Because the snowpack of the low basal area levels is more exposed to direct solar radiation and advective heat during the daytime, these two factors were probably more important than longwave radiation in the melt processes under

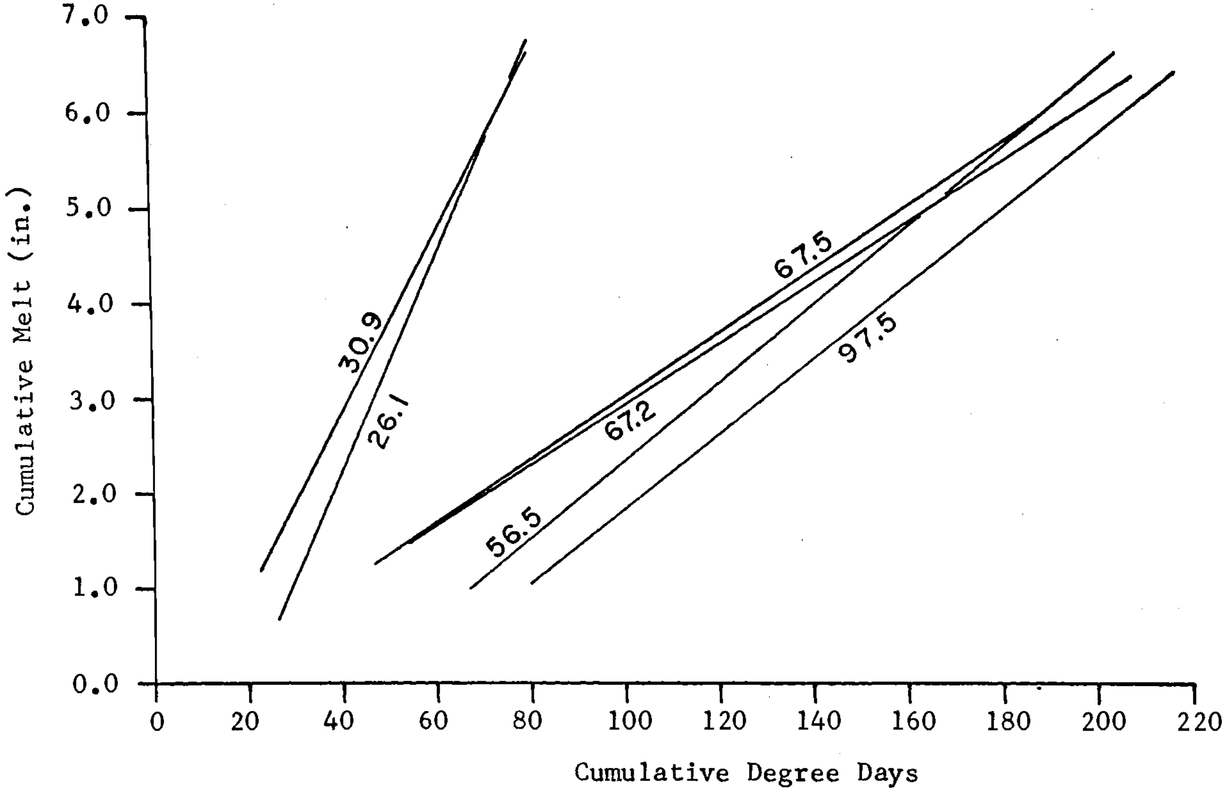


Figure 10. Cumulative melt versus cumulative melt degree days.

TABLE 8

CUMULATIVE MELT AND CUMULATIVE MELT DEGREE DAYS

Basal Area in Square Feet Per Acre	Date	Melt in Inches	Melt Degree Days
97.5	2-10-68	1.05	51.67
	2-17-68	1.40	90.50
	2-25-68	3.80	165.50
	3- 2-68	5.75	201.80
	To End	6.40	215.24
67.5	2-10-68	1.30	44.75
	2-17-68	1.95	76.42
	2-25-68	4.25	131.04
	3- 2-68	5.35	164.62
	To End	5.90	189.74
67.2	2-10-68	1.40	39.42
	2-17-68	1.60	79.09
	2-25-68	4.35	148.21
	3- 2-68	6.10	198.50
	To End	6.35	206.22
56.5	2-10-68	1.05	46.81
	2-17-68	1.30	82.39
	2-25-68	4.65	150.60
	3- 2-68	6.15	194.35
	To End	6.60	201.98
30.9	2-10-68	1.75	16.42
	2-17-68	1.30	34.09
	2-25-68	4.60	60.55
	3- 2-68	6.45	78.76
	To End	6.50	78.76

these stands. Miller (1950) suggested that shortwave radiation is an important energy source for snowpack ablation.

The degree day factor (i.e., the ratio of inches of snowmelt to melt degree days) is presented in Table 9 for selected plots in Taylor Woods. No consistent relationship exists between basal area and the melt degree day factor. However, the two stands of less than 50.0 square feet per acre had a degree day factor ranging from 0.101 to 0.137 for the two periods of most rapid melt. The other seven stands above 50.0 square feet per acre had a smaller degree day factor ranging from 0.034 to 0.071. These melt degree day factors are within the range of 0.03 to 0.66 inches melt per degree day found by Kittredge (1953), but an exponential relationship, as he found, was not evident. Also, there was no distinguishable linear relationship between cumulative melt and cumulative melt degree days as Kittredge (1953) reported.

The relationship between basal area and melt degree days appeared to be quadratic and is best exemplified during the melt period of February 19, 1968, through February 25, 1968 (Figure 11). Since temperature was recorded at only five basal area levels, no attempt was made to describe the relationship by an equation.

The Duncan's New Multiple Range test was used to aid interpretation of the results during the melt phase (Tables 10 and 11). The hypothesis tested was that water equivalents under all basal area levels are equal. The test indicated a poor relationship between water equivalent remaining in the snowpack and basal area until the period of most rapid melt. Even then, only two stocking levels can be roughly

TABLE 9

MELT DEGREE DAY FACTOR FOR TAYLOR WOODS (WINTER 1967-68)

Basal Area (Square feet per acre)	Date			
	2-10-68	2-17-68	2-25-68	3-2-68
26.1	.040	.014	.117	.137
30.9	.106	-.025	.124	.101
54.4	.022	.006	.041	.035
56.5	.023	.007	.049	.034
64.6	.020	-.006	.044	.036
67.1	.035	.005	.040	.035
67.5	.011	.021	.044	.056
71.0	.036	-.017	.049	.071
97.5	.020	.009	.032	.055

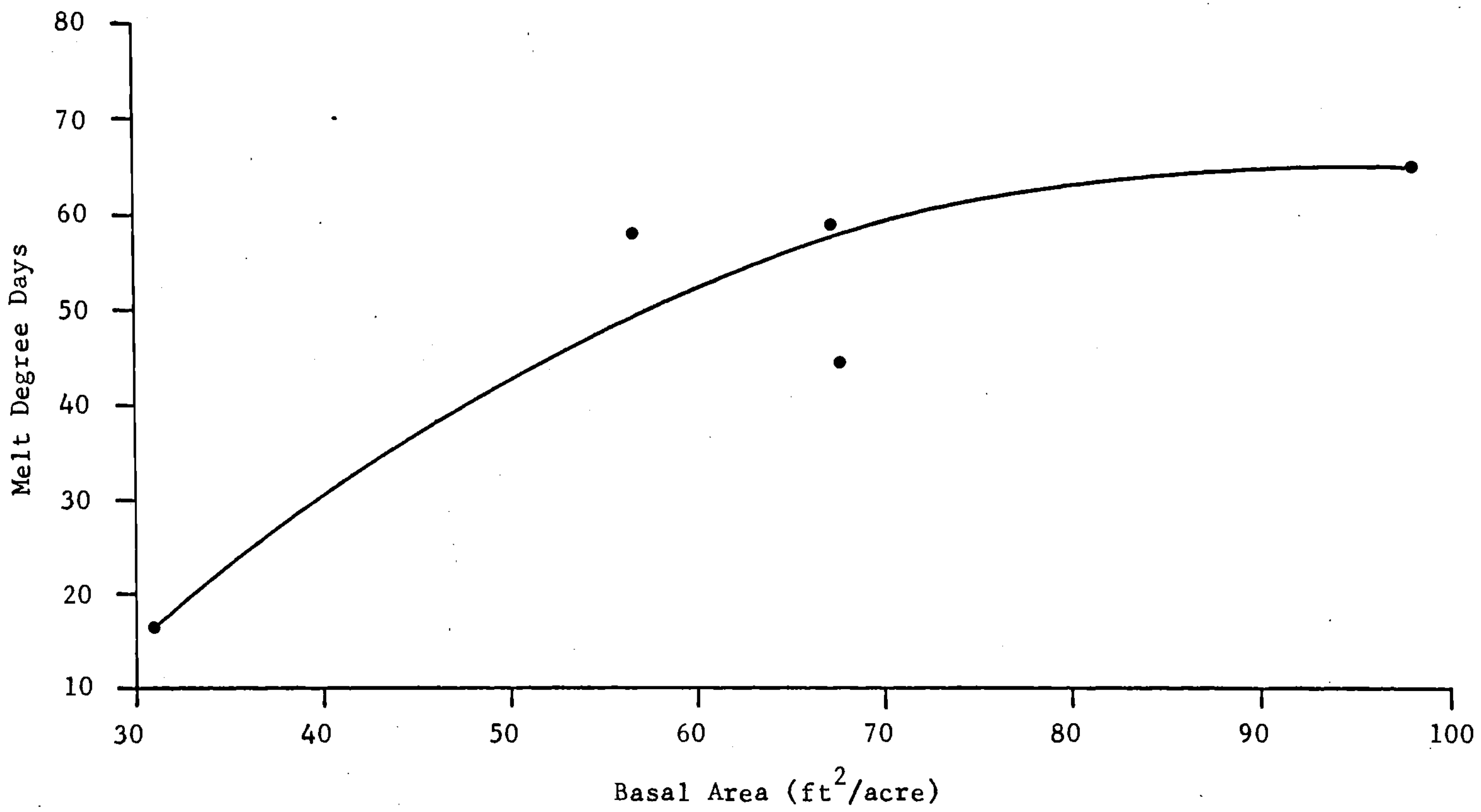


Figure 11. Melt degree days versus basal area.

2-19-68 to 2-25-68

TABLE 10

DUNCAN'S NEW MULTIPLE RANGE TEST COMPARING SNOW WATER EQUIVALENTS (W.C.)
UNDER VARIOUS BASAL AREA (B.A.) LEVELS (a)

January 30, 1968

B.A.	71.0	0.0	54.4	26.1	76.1	75.5	56.5	0.0	67.5	30.9	64.6	97.5	67.2	0.0	33.5	54.0
W.C.	7.50	7.10	7.05	6.75	6.70	6.65	6.60	6.55	6.50	6.45	6.45	6.40	6.35	6.17	6.05	5.75

February 10, 1968

B.A.	0.0	26.1	0.0	54.4	71.0	0.0	67.5	75.5	64.6	76.1	56.5	97.5	33.5	67.2	30.9
W.C.	6.45	6.10	6.05	6.00	5.90	5.90	5.84	5.70	5.65	5.65	5.55	5.35	5.00	4.95	4.75

TABLE 11

DUNCAN'S NEW MULTIPLE RANGE TEST COMPARING SNOW WATER EQUIVALENTS (W.C.) UNDER VARIOUS BASAL AREA (B.A.) LEVELS (b)

February 18, 1968

B.A.	71.0	76.1	0.0	0.0	64.6	26.1	54.4	75.5	0.0	56.5	30.9	67.5	97.5	67.2
W.C.	6.45	6.30	6.15	6.00	5.90	5.85	5.80	5.50	5.50	5.30	5.20	5.20	5.00	4.75

February 25, 1968

B.A.	71.0	76.1	75.5	54.4	64.6	26.1	67.5	97.5	0.0	67.2	56.5	30.9	0.0	0.0
W.C.	3.75	3.75	3.20	3.00	2.85	2.75	2.75	2.60	2.35	2.00	1.95	1.90	1.80	1.30

March 2, 1968

B.A.	76.1	54.4	71.0	75.5	64.6	67.5	97.5	0.0	56.5	30.9	26.1	67.2	0.0	0.0
W.C.	1.68	1.43	1.39	1.01	0.96	0.86	0.68	0.56	0.43	0.40	0.26	0.26	0.13	0.0

separated. The snowpack disappeared in all stands with less than 50.0 square feet of basal area only two to three days earlier than in stands with more than 50.0 square feet of basal area. This difference was statistically different (Table 10). However, some plots with greater than 50.0 square feet per acre also had a rapid melt rate. Water equivalent remaining under various stocking levels during the melt period showed only a weak relationship with basal area.

CONCLUSIONS

It appears that the stand density of ponderosa pine in the Flagstaff area had no influence on the amount of snow reaching the forest floor during the winter of 1967-68. Analysis of the snowmelt during the winter of 1968 suggests that stand density of ponderosa pine may affect snowmelt. Stand density levels less than 50.0 square feet per acre had a melt rate slightly higher than stand density levels greater than 50.0 square feet per acre. To increase melt rates for the Flagstaff area, it may be advantageous to maintain stocking levels of less than 50.0 square feet per acre. These conclusions are based on data for only one winter and require further investigation.

APPENDIX A

OTHER METHODS OF ANALYSIS AND SAMPLING TECHNIQUES

Analysis of the data for the accumulation phase included quadratic models, interaction models and combinations of quadratic and interaction models using variables of snow depth, water equivalent, and snow density. None were successful in accounting for more of the variation than is shown in Tables 5B through 8B (Appendix B).

Analysis of the melt phase also included several different models and variables. Degree days, calculated as the number of hours above 32°F, was unsuccessfully used as a variable in both the basal area prediction model and the snowmelt prediction model. Melt degree days, which include both intensity and duration of temperature, is a better temperature index. Melt rates per day gave poorer results than melt loss between measurement periods when used as a variable in the prediction equations. In predicting melt loss, snowpack density accounted for only a slight amount of variance. Interactions between basal area and density, and melt degree days and density, gave only slight increases in the coefficient of determination.

Determination of the number of samples needed per plot was made at the 95 percent confidence interval. The results (Appendix A, Table 1A) showed that up to the last two measurement periods, 10 samples per plot were sufficient to determine water equivalent within ± 0.5 inch. On the last measurement date, the variance was so great that it would be impractical to get a good estimate of the mean water equivalent.

On December 27, 1967, a series of systematic and random samples were taken to determine if there is a difference between these

TABLE 1A

AVERAGE NUMBER OF SAMPLE POINTS PER PLOT NEEDED DURING MELT PERIOD

Date	No. Plots Needed
1-30-68	0.3
2-10-68	0.8
2-17-68	1.9
2-25-68	13.7
3- 2-68	48.9

methods. A test of homogeneity of variance indicated that the two sampling methods produced similar results in estimating water equivalent in all but one case (Appendix A, Table 2A). Because of the ease of a systematic sampling, compared to random sampling designs, it may be used to advantage with no increase in the variance of the measurements. Kittredge (1953) compared systematic and random snow sampling for two years in the Sierra Nevada mountains and found no significant difference between the two methods. A random sample may not be necessary to obtain precise results. This point warrants further verification.

TABLE 2A

TEST OF VARIANCE OF WATER CONTENT ON DECEMBER 27, 1967, FOR SYSTEMATIC AND RANDOM SAMPLING METHODS

Basal Area	Random Sample Variance	Degrees of Freedom	Systematic Sample Variance	Variance Ratio.	F Tab. at λ=.10	Conclusion
76.1	0.100	9	0.861	8.610	2.44	Reject
0.0	0.250	9	0.122	2.049	2.44	Accept
56.5	0.283	9	0.456	1.611	2.44	Accept
67.2	0.305	9	0.444	1.456	2.44	Accept
30.9	0.532	19	0.550	1.034	1.79	Accept
97.5	0.117	9	0.306	2.615	2.44	Accept

APPENDIX B

RESULTS OF STEPWISE MULTIPLE LINEAR REGRESSION DURING THE MELT PHASE

TABLE 1B

STEPWISE MULTIPLE REGRESSION ANALYSIS PREDICTING BASAL AREA LEVEL FOR MAXIMUM MELT RATE JANUARY 30, 1968, TO FEBRUARY 10, 1968

Step	Variable Entering	Partial Regression Coefficient	Standard Error of Coefficient	Y Intercept	Standard Error of Y	Coefficient of Determination	F Ratio
1	$(M.D.D.)^2$	0.023346	0.000957	24.495	7.862	0.8634	594.52*
2	$(M.D.D.)^2$	0.023836	0.000985	19.504	7.770	0.8680	305.98*
	M.R.	4.255217	2.362574	"	"	"	"
3	$(M.D.D.)^2$	0.023543	0.001037	14.054	7.777	0.8692	203.90*
	M.R.	16.07859	13.15243	"	"	"	"
	$(M.R.)^2$	-5.336198	5.839307	"	"	"	"
4	$(M.D.D.)^2$	0.020317	0.007206	11.430	7.811	0.8695	151.66*
	M.R.	15.52926	13.26533	"	"	"	"
	$(M.R.)^2$	-5.052577	5.898120	"	"	"	"
	M.D.D.	0.210085	0.464344	"	"	"	"
5	$(M.D.D.)^2$	0.020483	0.007255	12.099	7.844	0.8697	120.19*
	M.R.	16.86624	13.82323	"	"	"	"
	$(M.R.)^2$	-5.700548	6.18665	"	"	"	"
	M.D.D.	0.191356	0.469386	"	"	"	"
	$(Den.)^2$	-7.239132	19.83552	"	"	"	"
6	$(M.D.D.)^2$	0.020448	0.007289	9.296	7.885	0.8699	99.26*
	M.R.	16.56406	13.90771	"	"	"	"
	$(M.R.)^2$	-5.488326	6.237471	"	"	"	"
	M.D.D.	0.190667	0.471582	"	"	"	"
	$(Den.)^2$	-33.47085	67.58343	"	"	"	"
	Den.	17.89758	44.06114	"	"	"	"

* Indicates significance at the 1% level.

TABLE 2B

STEPWISE MULTIPLE REGRESSION ANALYSIS PREDICTING BASAL AREA LEVEL FOR MAXIMUM MELT RATE FEBRUARY 10, 1968, TO FEBRUARY 18, 1968

Step	Variable Entering	Partial Regression Coefficient	Standard Error of Coefficient	Y Intercept	Standard Error of Y	Coefficient of Determination	F Ratio
1	M.D.D.	1.963239	0.129119	-3.442	11.441	0.7109	231.18*
2	M.D.D.	2.014580	0.110336	-11.414	9.747	0.7924	177.49*
	(M.R.)^2	51.05162	8.450522	"	"	"	"
3	M.D.D.	-2.700933	1.683072	44.196	9.406	0.8087	129.71*
	(M.R.)^2	71.24481	10.87337	"	"	"	"
	(M.D.D.)^2	0.084650	0.030153	"	"	"	"
4	M.D.D.	-3.000626	1.677338	47.614	9.319	0.8143	99.79*
	(M.R.)^2	74.70925	10.97508	"	"	"	"
	(M.D.D.)^2	0.089587	0.030023	"	"	"	"
	M.R.	4.646700	2.813727	"	"	"	"
5	M.D.D.	-3.04477	1.690279	49.820	9.364	0.8145	79.08*
	(M.R.)^2	74.19210	11.12843	"	"	"	"
	(M.D.D.)^2	0.090176	0.030217	"	"	"	"
	M.R.	4.675671	2.828648	"	"	"	"
	(Den)^2	-10.54390	30.33965	"	"	"	"
6	M.D.D.	-3.116868	1.712471	48.072	9.411	0.8148	65.27*
	(M.R.)^2	74.27760	11.18678	"	"	"	"
	(M.D.D.)^2	0.091282	0.030549	"	"	"	"
	M.R.	4.579769	2.857318	"	"	"	"
	(Den.)^2	-39.92167	93.45031	"	"	"	"
	Den.	18.65422	56.09148	"	"	"	"

* Indicates significance at the 1% level.

TABLE 3B

STEPWISE MULTIPLE REGRESSION ANALYSIS PREDICTING BASAL AREA LEVEL FOR MAXIMUM MELT RATE FEBRUARY 18, 1968, TO FEBRUARY 25, 1968

Step	Variable Entering	Partial Regression Coefficient	Standard Error of Coefficient	Y Intercept	Standard Error of Y	Coefficient of Determination	F Ratio
1	M.D.D.	0.947850	0.071994	5.270	11.926	0.6709	173.33*
2	M.D.D.	0.7038	0.053186	106.710	7.914	0.8568	251.31*
	M.R.	-30.30710	2.902609	"	"	"	"
3	M.D.D.	0.709329	0.045951	451.933	6.835	0.8944	234.44*
	M.R.	-274.0253	44.87177	"	"	"	"
	(M.R.)^2	42.42247	7.798342	"	"	"	"
4	M.D.D.	0.714161	0.046570	456.268	6.855	0.8951	174.94*
	M.R.	-278.3280	45.39750	"	"	"	"
	(M.R.)^2	43.20219	7.895671	"	"	"	"
	Den.	3.653129	5.073421	"	"	"	"
5	M.D.D.	0.707829	0.046506	460.596	6.814	0.8976	142.05*
	M.R.	-281.5717	45.18198	"	"	"	"
	(M.R.)^2	43.75738	7.857867	"	"	"	"
	Den.	30.51246	19.65855	"	"	"	"
	(Den.)^2	-61.61232	43.58561	"	"	"	"
6	M.D.D.	0.529024	0.397775	459.065	6.848	0.8978	117.25*
	M.R.	-277.5165	46.28080	"	"	"	"
	(M.R.)^2	43.00313	8.070608	"	"	"	"
	Den.	30.96670	19.78122	"	"	"	"
	(Den.)^2	-63.05339	43.91667	"	"	"	"
	(M.D.D.)^2	0.001803	0.003982	"	"	"	"

* Indicates significance at the 1% level.

TABLE 4B

STEPWISE MULTIPLE REGRESSION ANALYSIS PREDICTING BASAL AREA LEVEL FOR MAXIMUM MELT RATE FEBRUARY 25, 1968, TO MARCH 2, 1968

Step	Variable Entering	Partial Regression Coefficient	Standard Error of Coefficient	Y Intercept	Standard Error of Y	Coefficient of Determination	F Ratio
1	M.D.D.	1.096236	0.151534	18.767	16.401	0.3838	52.33*
2	M.D.D.	8.028317	0.786014	-82.825	11.799	0.6849	90.21*
	$(M.D.D.)^2$	-0.102976	0.011563	"	"	"	"
3	M.D.D.	10.56090	0.673651	-146.780	8.914	0.8223	126.50*
	$(M.D.D.)^2$	-0.163053	0.011543	"	"	"	"
	M.D.D.x M.R.	0.966343	0.121355	"	"	"	"
4	M.D.D.	5.204663	0.702296	18.209	6.003	0.9204	234.16*
	$(M.D.D.)^2$	-0.151142	0.007864	"	"	"	"
	M.D.D.x M.R.	3.306276	0.248057	"	"	"	"
	M.R.	-75.67679	7.574621	"	"	"	"
5	M.D.D.	3.225522	0.783542	138.632	5.437	0.9354	232.05*
	$(M.D.D.)^2$	-0.142198	0.007417	"	"	"	"
	M.D.D.x M.R.	4.121529	0.293245	"	"	"	"
	M.R.	-180.7663	25.23966	"	"	"	"
	$(M.R.)^2$	22.43698	5.185826	"	"	"	"

* Indicates significance at the 1% level.

TABLE 5B

STEPWISE MULTIPLE REGRESSION ANALYSIS PREDICTING SNOW MELT FROM JANUARY 30, 1968, TO FEBRUARY 10, 1968

Step	Term Entering	Partial Regression Coefficient	Standard Error of Coefficient	Y Intercept	Standard Error of Y	Coefficient of Determination	F Ratio
1	M.D.D.	-0.007565	0.002641	1.276	0.338	0.0803	8.20*
2	M.D.D.	-1.920852	0.006781	1.237	0.334	0.1132	5.94*
	B.A.	0.007863	0.004213	"	"	"	"
3	M.D.D.	-0.013759	0.007986	0.862	0.333	0.1288	4.53*
	B.A.	0.020598	0.010815	"	"	"	"
	B.A.x M.D.D.	-0.000242	0.000189	"	"	"	"
4	M.D.D.	-0.170388	0.044790	0.778	0.313	0.2346	6.97*
	B.A.	0.110454	0.027304	"	"	"	"
	B.A.x M.D.D.	-0.002198	0.000580	"	"	"	"
	$(M.D.D.)^2$	0.003471	0.000979	"	"	"	"
5	M.D.D.	-0.010618	0.045001	-0.651	0.261	0.4727	16.14*
	B.A.	0.084715	0.023142	"	"	"	"
	B.A.x M.D.D.	-0.010988	0.004610	"	"	"	"
	$(M.D.D.)^2$	0.007624	0.001045	"	"	"	"
	$(B.A.)^2$	0.003051	0.000479	"	"	"	"

* Indicates significance at 1% level.

TABLE 6B

STEPWISE MULTIPLE REGRESSION ANALYSIS PREDICTING SNOW MELT FROM FEBRUARY 10, 1968, TO FEBRUARY 18, 1968

Step	Term Entering	Partial Regression Coefficient	Standard Error of Coefficient	Y Intercept	Standard Error of Y	Coefficient of Determination	F Ratio
1	B.A.x M.D.D.	0.000056	0.000034	-0.043	0.347	0.0281	2.72
2	B.A.x M.D.D.	0.000269	0.000726	0.160	0.346	0.0443	2.15
	B.A.	-0.010697	0.008515	"	"	"	"
3	B.A.x M.D.D.	0.000382	0.000178	0.706	0.339	0.0889	2.99*
	B.A.	-0.033858	0.013751	"	"	"	"
	$(B.A.)^2$	0.000151	0.000071	"	"	"	"
4	B.A.x M.D.D.	-0.001877	0.000899	-0.544	0.330	0.1502	4.02*
	B.A.	-0.053943	0.015486	"	"	"	"
	$(B.A.)^2$	0.000834	0.000275	"	"	"	"
	M.D.D.	0.136292	0.053217	"	"	"	"
5	B.A.x M.D.D.	0.006302	0.003721	-1.320	0.322	0.1958	4.38*
	B.A.	-0.148049	0.044279	"	"	"	"
	$(B.A.)^2$	-0.000558	0.000672	"	"	"	"
	M.D.D.	0.359152	0.111437	"	"	"	"
	$(M.D.D.)^2$	-0.010919	0.004827	"	"	"	"

* Indicates significance at 1% level.

TABLE 7B

STEPWISE MULTIPLE REGRESSION ANALYSIS PREDICTING SNOW MELT FROM FEBRUARY 18, 1968, TO FEBRUARY 25, 1968

Step	Term Entering	Partial Regression Coefficient	Standard Error of Coefficient	Y Intercept	Standard Error of Y	Coefficient of Determination	F Ratio
1	$(B.A.)^2$	-0.000099	0.000009	3.279	0.213	0.5775	116.20*
2	$(B.A.)^2$	-0.000127	0.000013	3.193	0.204	0.6190	68.24*
	$(M.D.D.)^2$	0.000055	0.000018	"	"	"	"
3	$(B.A.)^2$	-0.000129	0.000012	4.125	0.185	0.6914	61.99*
	$(M.D.D.)^2$	0.000505	0.000103	"	"	"	"
	M.D.D.	-0.044365	0.010054	"	"	"	"
4	$(B.A.)^2$	-0.000463	0.000132	4.592	0.179	0.7138	51.14*
	$(M.D.D.)^2$	0.001171	0.000281	"	"	"	"
	M.D.D.	-0.121648	0.031999	"	"	"	"
	B.A.	0.048613	0.019174	"	"	"	"
5	$(B.A.)^2$	-0.000011	0.000206	5.086	0.172	0.7391	45.89*
	$(M.D.D.)^2$	0.002713	0.000613	"	"	"	"
	M.D.D.	-0.200014	0.041579	"	"	"	"
	B.A.	0.097977	0.025501	"	"	"	"
	B.A.x M.D.D.	-0.001695	0.000605	"	"	"	"

* Indicates significance at 1% level.

TABLE 8B

STEPWISE MULTIPLE REGRESSION ANALYSIS PREDICTING SNOW MELT FROM FEBRUARY 25, 1968, TO MARCH 2, 1968

Step	Term Entering	Partial Regression Coefficient	Standard Error of Coefficient	Y Intercept	Standard Error of Y	Coefficient of Determination	F Ratio
1	B.A.	-0.007117	0.001808	2.160	0.346	0.1557	15.49*
2	B.A.	-0.062119	0.005857	3.590	0.239	0.6005	62.38*
	$(B.A.)^2$	0.00465	0.000048	"	"	"	"
3	B.A.	-0.122183	0.004603	4.760	0.115	0.9078	269.40*
	$(B.A.)^2$	0.007434	0.000029	"	"	"	"
	B.A.x M.D.D.	0.000553	0.000033	"	"	"	"
4	B.A.	-0.139287	0.006435	5.085	0.108	0.9204	234.29*
	$(B.A.)^2$	0.000423	0.000094	"	"	"	"
	B.A.x M.D.D	0.002242	0.000437	"	"	"	"
	$(M.D.D.)^2$	-0.001329	0.000372	"	"	"	"
5	B.A.	-0.151724	0.016409	5.052	0.108	0.9211	186.82*
	$(B.A.)^2$	0.000364	0.000118		"	"	"
	B.A.x M.D.D.	0.002776	0.000803	"	"	"	"
	$(M.D.D.)^2$	-0.00201	0.000906	"	"	"	"
	M.D.D.	0.020949	0.025417	"	"	"	"

* Indicates significance at 1% level.

LITERATURE CITED

Anderson, Henry W. 1956. Forest cover effects on snow accumulation and melt. Trans. Amer. Geophys. Union. 37(3):307-312.

Anderson, Henry W. 1960. Prospects for affecting the quantity and timing of water yield through snowpack management in California. 28th Ann. Proc. Western Snow Conference. pp. 44-50.

Anderson, Henry W. 1963. Managing California's snow zone lands for water. Pac. S.W. For. and Range Exp. Sta. Res. Paper 6.

Anderson, Henry W., and C. H. Gleason. 1960. Effects of logging and brush removal on snow water runoff. Abstract of Pub. 51 I.A.S.H. Commission of Surf. Waters. pp. 478-489.

Anderson, Henry W., R. M. Rice, and A. J. West. 1958. Forest shade related to snow accumulation. 26th Ann. Proc. Western Snow Conf. pp. 21-31.

Berndt, Herbert W. 1961. Some influences of timber cutting on snow accumulation in the Colorado front range. Rocky Mt. For. and Range Exp. Sta. Res. Note 58.

Church, J. E. 1912. The conservation of snow: its dependence on forests and mountains. Sci. Amer. Sup. 74:145-155.

Connaughton, C. A. 1935. The accumulation and rate of melting of snow as influenced by vegetation. J. For. 33:564-569.

Enz, R. W. 1964. Summary of snow survey measurements for Arizona 1938-1964. U.S.D.A. Soil Conserv. Ser. p. 17.

Enz, R. W. Jan. 1968a. Water supply outlook for Arizona. U.S.D.A. Soil Conserv. Ser. pp. 1-11.

Enz, R. W. Feb. 1968b. Water supply outlook for Arizona. U.S.D.A. Soil Conserv. Ser. pp. 1-11.

Ffolliott, P. F., E. A. Hansen, and A. D. Zander. 1965. Snow in natural openings and adjacent ponderosa pine stands on the Beaver Creek Watersheds. Rocky Mt. For. and Range Exp. Sta. Res. Note 53.

Goodell, B. C. 1952. Watershed management aspects of thinned young lodgepole pine stands. J. For. 50:374-378.

Hoover, Marvin D. 1960. Prospects for affecting the quantity and timing of water yield through snowpack management in the southern Rocky Mountains. 28th Ann. Proc. Western Snow Conf. pp. 51-53.

Jaenicke, A. J., and M. H. Foerster. 1915. The influence of a western yellow pine forest on the accumulation and melting of snow. Mo. Weath. Rev. 43:115-126.

Kittredge, Joseph. 1953. Influences of forests on snow in the ponderosa-sugar pine-fir zone of the Central Sierra Nevada. Hilgardia. 22(1).

Li, C. C. 1956. The concept of path coefficient and its impact on population genetics. Biometrics 12(2):190-209.

Love, L. D. 1953. Watershed management in the Colorado Rockies. J. Soil and Water Conserv. 8:374-378.

Ludlum, D. M. 1968. The snowfall season of 1966-67. Weatherwise 21(1):26-32.

Miller, David H. 1950. Insolation and snowmelt in the Sierra Nevada. Bull. Amer. Meteor. Soc. 31(8):295-299.

Miller, David H. 1966. Transport of intercepted snow from trees during snow storms. Pac. S.W. For. and Range Exp. Sta. Res. Paper 33.

Pearson, G. H. 1913. A meteorological study of parks and timbered areas in the western yellow pine forests of Arizona and New Mexico. Mo. Weath. Rev. 41:1615-1627.

Rothacher, Jack. 1965. Snow accumulation and melt in strip cuttings on the west slope of the Oregon Cascades. Pac. N.W. For. and Range Exp. Sta. Res. Note 23.

Satterlund, D. R., and H. F. Haupt. 1967. Snow catch by conifer crowns. Water Resources Res. 3(4):1035-1039.

Sellers, William D. 1960. Arizona Climate. The University of Arizona Press. pp. 1-60.

Wilm, H. G., and M. H. Collet. 1940. The influence of a lodgepole pine forest on storage and melting of snow. Trans. Amer. Geophys. Union 2:505-508.

Wilm, H. G., and E. G. Dunford. 1948. Effect of timber cutting on water available for streamflow from a lodgepole pine forest. U.S.D.A. Tech. Bull. 968.

Work, R. A., H. J. Stockwell, T. G. Freeman, and R. T. Beaumont. 1965. Accuracy of field snow surveys. U.S.D.A. Soil Conserv. Ser. Tech. Report 163.