

A TIME-SPACE TECHNIQUE TO ANALYZE SNOWPACKS IN  
AND ADJACENT TO OPENINGS IN THE FOREST

by

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## ABSTRACT

A general technique was developed to enable the land manager to predict the "net" effect of an opening on the snowpack in and adjacent to that opening at any given location at any point in time. The technique was illustrated by collecting data at seven study sites located in the ponderosa pine type of Arizona on 10 measurement dates. Multiple regression analyses utilizing these data produced several significant equations (at the  $\alpha = .01$  level) for predicting the "net" effect of an opening in the ponderosa pine type of Arizona.

In addition, the significant equations yielded site information, within the range of conditions studied, which could be utilized to maximize or minimize the "net" effect of openings, depending upon the desired land management objectives. Knowledge of these site variables could aid the land manager in decisions concerning the location and size of proposed timber cuts in situations where water yield from snowpacks is an important consideration.

## INTRODUCTION

In Arizona, as in other arid regions, ways of increasing the amount of water available for man's use are being sought. Since much of Arizona's runoff is derived from snowmelt in the ponderosa pine (Pinus ponderosa Laws.) type, these high elevation forests have been one focal point of study.

Timber is a valuable commodity. When man harvests it, he has a variety of openings with regard to shape and size which he can create in the forest. Four common methods of timber removal are (1) clearcutting, (2) blockcutting, (3) stripcutting, and (4) selective cutting. Clearcutting is the removal of the entire stand of timber in one cut. Block and strip cutting are two forms of clearcutting and are differentiated by their dimensions. A block cut is usually one of equal dimensions while a strip cut is more of a long rectangular shape. Selective cutting is the removal of mature timber, usually the oldest or largest trees, as single scattered trees.

Whenever a large percentage of the existing timber is removed from an area, regardless of the manner of removal, the snowpack is affected during its periods of accumulation and melt. In the type of selection cut described above, snow accumulation has been found to

increase as some function of the reduction in forest density (Lull and Rushmore, 1960). Also, the rate of melt is found to be increased as the density of the stand is reduced (Lull and Rushmore, 1960).

The various forms of clearcutting all create openings of some shape and size in the forest. It has long been known that snow accumulates more in forest openings than in the surrounding denser forest (Mattoon, 1909; Church, 1912; Jaenicke and Foerster, 1915; Wilm and Dunford, 1948; Kittredge, 1948; Anderson, 1956; Sartz and Trimble, 1956; Anderson and Gleason, 1959; Weitzman and Bay, 1959; Love and Goodell, 1960; Berndt, 1965; Hoover and Leaf, 1967; Hansen and Ffolliott, 1968). The reason for this increased snow accumulation in openings within forested conditions is usually attributed to: (1) wind patterns during and after the precipitation event (Pearson, 1913; Geiger, 1965; Miller, 1966; Goodell, 1966; Hoover and Leaf, 1967), and (2) the lack of a forest canopy to intercept the falling snow (Kittredge, 1953; Goodell, 1966), although some studies have minimized interception losses (Love, 1955; Hoover and Leaf, 1967; Satterlund and Haupt, 1970). Besides increased snow accumulation, another observed effect of an opening during the accumulation phase is the formation of a trough in the snow profile under forest canopies near its windward side (Anderson and Gleason, 1960; Hansen and Ffolliott, 1968).

Any opening created in the forest also affects the melt characteristics of the snowpack in and around the opening. Wind movement patterns are changed along with turbulence effects (Goodell, 1966). In response to these changes, sensible heat transfer, vapor pressure gradients, and convective processes all may be altered. The area where timber has been removed may be more open to direct solar radiation penetration, yet there are fewer trees to absorb and reradiate this short-wave radiation as long-wave radiation. Thus, the removal of trees affects several processes simultaneously (Anderson, 1967). Other, more specific effects of creating openings have also been noted. Field studies have shown higher melt rates in the open along the north side of east-west clearcut strips than in the open along the south side (Weitzman and Bay, 1959; Rothacher, 1965; Hansen and Ffolliott, 1968). Shaded sides of openings do not receive as much direct beam solar radiation as do exposed sides. Also, more short-wave radiation may penetrate onto a snowpack under the forest to the north of an opening than under a forest to the south of that opening (Sartz and Trimble, 1956). Currently, one way of determining the amount of melt from a snowpack is by means of energy budget analysis. The energy budget is an accounting of all forms of energy that enter, leave, or are contained within a surface.

To achieve maximum length of duration of the known increased snow accumulation in openings, it was first thought that the openings should be small enough to be continually shaded (Church, 1912), and that their optimum diameter should be approximately equal to the height of the surrounding trees in dense, coniferous forest (Wilm and Collet, 1940; Niederhof and Dunford, 1942; Kittredge, 1948; Colman, 1953). Initial findings had led to the conclusion that a dense forest honeycombed with many small openings would be most efficient in accumulating and conserving snow. However, it is well known that similar openings on different slope-aspect combinations receive different amounts of solar radiation and, therefore, have different energy budgets and corresponding melt characteristics. Thus, later studies showed that the early idea of the forest honeycombed with small openings would indeed provide most efficient snow storage on warm, exposed south slopes, but for this same maximum efficiency, large openings should perhaps be used on cool, shady north slopes (Wilm and Collet, 1940; Haupt, 1951; Lassen, Lull, and Frank, 1952).

It is apparent from the previous discussion that the creation of an opening in the forest affects the snowpack during its accumulation and melt phases. It should also be noted that many of the processes that are involved in these phases are complex and not yet fully understood. At any point in time, a snowpack profile is the integrated result

of all accumulation, redistribution, and melt processes that have taken place prior to the time of measurement. Many studies have been conducted in an attempt to explain the variation of snowpack water equivalent on-site at a given point in time, often at peak accumulation (Anderson, 1956, 1967; Anderson and Pagenhart, 1957; Packer, 1962; Ffolliott and Hansen, 1968). Variables and parameters that are of importance when trying to evaluate the effect of an opening on snowpack accumulation and melt include, but are not inclusive of, the following.

The following factors affect snowpack accumulation:

1. Wind speed. This variable may also cause redistribution of the snowpack both during and after a precipitation event.
2. Density and height of the timber surrounding the opening. This variable not only affects wind speed (Bates and Stoeckeler, 1941) but also wind patterns and eddies.
3. Orientation of the opening. This variable is particularly important regarding strip cuts (Hansen and Ffolliott, 1968; Clausen and Mace, 1972).

Maximum snowfall catchment results when the wind direction is perpendicular to the long axis of the strip during the precipitation event.

4. Size of the opening. The most efficient increased snowfall accumulations are found in openings with

diameters or strips with widths of 1 to 2 times the tree height of the surrounding timber.

5. Total amount of precipitation. This variable determines, in part, the magnitude of the effects caused by the opening.
6. Elevation. Generally, this variable is used as an indicator of precipitation.

The following factors affect snowpack melt:

1. Short-wave radiation received and reflected by snowpack. The albedo of the snowpack determines the percentage of the incident short-wave radiation that is reflected.
2. Long-wave radiation received and emitted by snowpack. Almost all of the long-wave radiation received by a snowpack is absorbed.
3. Vapor pressure gradients between snow surface and overlying atmosphere. These gradients are used to determine the amount of evaporation or condensation that is occurring. The relative humidity is often used in an attempt to evaluate these gradients.
4. Temperature gradients between snow surface and overlying atmosphere. These gradients are used to evaluate sensible heat transfer. Heat conduction from the ground to the snowpack is almost always ignored.

5. Wind speed and turbulence. These parameters are used in conjunction with empirical coefficients and vapor pressure and temperature gradients to form equations describing convective and evaporative transport processes.
6. Rain. This variable contributes sensible heat to the snowpack.

Other variables are often used as indicators when exact measurements of the above mentioned melt variables and parameters are not possible. Slope-aspect combinations affect the magnitudes of incoming incident solar radiation (Frank and Lee, 1966). Tree height and density have marked effects on the long-wave radiation flux to and from the snowpack (Reifsnyder and Lull, 1965; Miller, 1966). The orientation of the opening, along with the previous parameters, determines the shading characteristics of the cut area and its surrounding forest (Anderson, 1967). Elevation is often used as an indication of the temperature regime at the area of interest.

Since snowpacks do not always have separate, distinct accumulation and melt phases (in fact, often do not in the ponderosa pine type in Arizona), and due to the complexity of many of the processes described above, it is difficult to predict what the effect of a cut will be on a snowpack regime in any given situation. However, a

two-dimensional technique was recently developed which gives a quantitative characterization of the effect that an opening has on the snowpack profile at a given point in time (Ffolliott and Thorud, 1972), although the individual effects of all the determinant processes can not be separated. Earlier studies had been primarily concerned with the increased accumulations observed within the opening itself. However, since there may also be areas of snowpack depletion caused by an opening, the analysis of the snowpack must take place in the surrounding forest as well as within the opening to get a "true" picture of the opening's "net" effect.

The recently developed two-dimensional technique attempts to assess the "net" effect of a forest opening on a snowpack profile by the use of a "zone of influence." This "zone" was defined as the area bounded by sample points to the windward and leeward of an opening which have measurable differences in snowpack water equivalent as compared to sample points farther from the opening (Hansen and Ffolliott, 1968). The sample points referred to were established at  $1/4-H$  ( $H$  = average height of surrounding timber) intervals along two parallel transects running across a strip cut and extending  $3-H$  into the adjacent forest overstory on either side.

An arbitrary rule of thumb was used to define the "measurable difference" above in order to delineate the

"zone of influence." This rule allows differences of 15 per cent in water equivalent to be attributed to spatial variations in forest overstories and measurement errors; thus, differences exceeding this value were considered to be due to the influence of the opening. Next, a Cartesian coordinate system was imposed on the snowpack profile with the Y-axis as the left-hand boundary of the "zone of influence" and the X-axis a reference line representing the "average" snowpack water equivalent without the effect of the clearcut strip. The delineation of both the "zone of influence" and the corresponding Cartesian coordinate system is illustrated in Figure 1. Data illustrated are the average of measurements obtained from each pair of sample points along the two parallel transects. Curve fitting procedures were then used to get the "best" statistical fit of the sampled data points corresponding to the snowpack water equivalent measurements in the "zone of influence." These data points had been previously assigned X,Y coordinates within the Cartesian system.

Once the best mathematical expression, a continuous curve, had been found, the curve was integrated to determine the areas below and above the X-axis. If the area below the X-axis exceeded the area above it, then the strip cut had a "negative" effect on the snowpack, i.e., less snowpack water equivalent was present at this time than there would have been if no strip cut existed. Conversely, if the area above

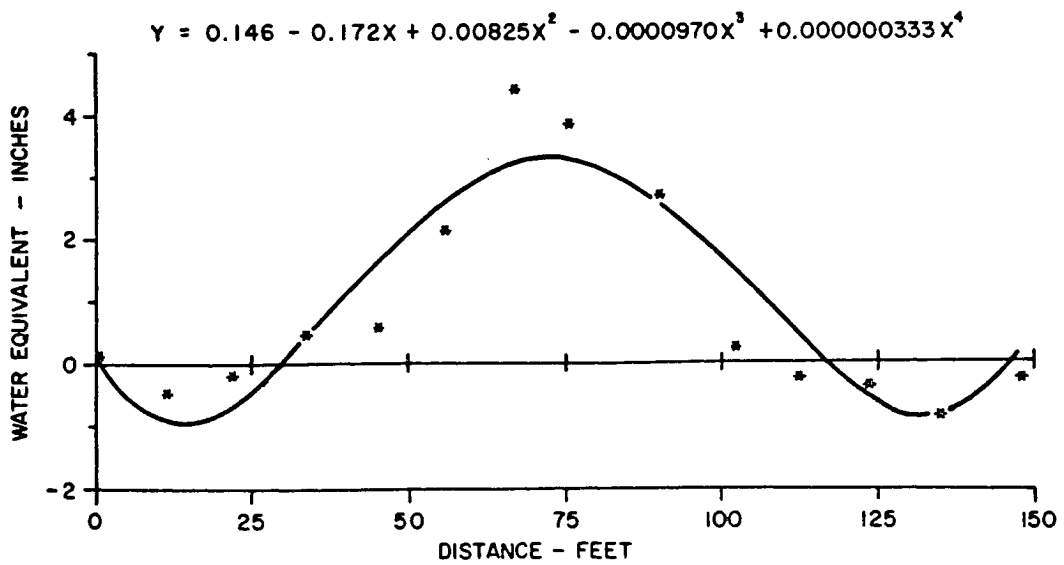
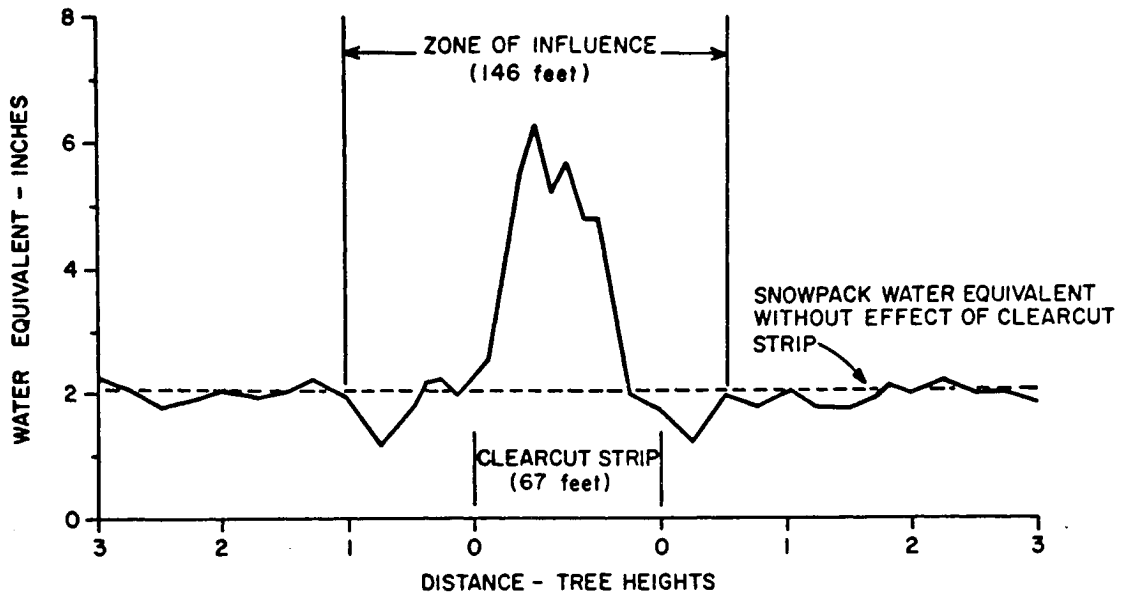


Figure 1. The delineation of the "zone of influence" and the corresponding Cartesian coordinate system.

the X-axis exceeded that below it, the strip cut had a "positive" effect at this point in time.

Although the two-dimensional technique has been used on only one site at one point in time (Ffolliott and Thorud, 1972), it was felt that subsequent analysis over an array of sites and for several points in time throughout a snow season might provide the land manager with quantitative information regarding the potential increase in snowpack water yield due to creating openings in forest overstories.

Thus, the study described herein is an attempt to develop a technique that will enable the resource manager to obtain this quantitative information. The practicing land manager generally has little access to complex and expensive instrumentation, especially that used to determine the wind measurements and long- and short-wave radiative fluxes which were shown to be important in snowpack dynamics earlier. Consequently, this study is constrained to using only readily available parameters in the development of the technique.

## DESCRIPTION OF STUDY

### Specific Objectives

The specific objective of this study was to develop, if possible, a technique that would enable the practicing land manager to predict the effect that an opening has on the snowpack in and adjacent to that opening at any point in time at any given location. The net effect of the opening is described in terms of the increase or decrease in the volume of water equivalent on-site as compared with the undisturbed forested condition.

### Study Areas

Seven study sites were established within the ponderosa pine type of Arizona. Three sites were located approximately 40 miles south of Flagstaff, while the remaining four were established in the White Mountains region. A list of these study sites with information concerning their location, vegetation, physiography, and sample design follows.

#### 1. Vespidae Site.

Location: approximately 10.1 miles south of Alpine, east side of Route 666 in the Apache National Forest.

Vegetation: ponderosa pine.

Physiography:

Slope: 5 per cent.

Aspect: southeast.

Elevation: 8100 feet.

Geologic formation: basalt (Qtb).

Type of opening: 2-H strip cut simulated by  
power line.

Sample design: two parallel measurement transects perpendicular to the edge of timber, each consisting of 49 sample points spaced 1/4-H apart.

2. Annex Site.

Location: approximately 7.5 miles south of Alpine, west side of Route 666 in the Apache National Forest.

Vegetation: ponderosa pine.

Physiography:

Slope: 5 per cent.

Aspect: northeast.

Elevation: 8000 feet.

Geologic formation: basalt (Qtb).

Type of opening: 1-3/4-H strip cut simulated by  
a natural opening.

Sample design: two parallel measurement transects perpendicular to the edge of timber, each consisting of 48 sample points spaced 1/4-H apart.

3. Hon-dah Site.

Location: approximately at intersection of Route 73 and Route 173 in the Fort Apache Indian Reservation.

Vegetation: ponderosa pine, with alligator juniper (Juniperus deppeana Steud.) intermixture.

Physiography:

Slope: 10 per cent.

Aspect: northwest.

Elevation: 7250 feet.

Geologic formation: basalt (Qtb).

Type of opening: 1-3/4-H strip cut simulated by a power line.

Sample design: two parallel transects perpendicular to the edge of timber, each consisting of 48 sample points spaced 1/4-H apart.

4. Navopache Site.

Location: approximately two miles northwest of Lakeside, west side of Route 173 in the Sitgreaves National Forest.

Vegetation: ponderosa pine, with alligator juniper intermixture.

Physiography:

Slope: 5 per cent

Aspect: northeast.

Elevation: 6600 feet.

Geologic formation: shale, sandstone, limestone  
(K<sub>s</sub>).

Type of opening: 1-1/2-H strip cut simulated by  
a power line.

Sample design: two parallel transects perpendicular  
to the edge of timber, each consisting of 47 sample  
points spaced 1/4-H apart.

5. East Strip Site.

Location: approximately 0.5 miles north of Happy  
Jack, east side of FH3 in the Coconino National  
Forest.

Vegetation: ponderosa pine, with Gambel oak  
(Quercus gambellii Nutt.) intermixture.

Physiography:

Slope: 15 per cent.

Aspect: east.

Elevation: 7500 feet.

Geologic formation: basalt (Qtb).

Type of opening: 1-3/4-H strip cut simulated by  
a past logging operation.

Sample design: two parallel transects perpendicular  
to the edge of timber, each consisting of 48 sample  
points spaced 1/4-H apart.

6. Upper APS Site.

Location: approximately one mile north of Happy Jack,  
west side of FH3 in the Coconino National Forest.

Vegetation: ponderosa pine, with Gambel oak and alligator juniper intermixture.

Physiography:

Slope: 0 per cent (15 per cent sideslope).

Aspect: none.

Elevation: 7500 feet.

Geologic formation: basalt (Qtb).

Type of opening: 1-1/2-H strip cut simulated by a power line.

Sample design: two parallel transects perpendicular to the edge of timber, each consisting of 47 sample points spaced 1/4-H apart.

7. Lower APS Site.

Location: see Upper APS site.

Vegetation: ponderosa pine, with Gambel oak and alligator juniper intermixture.

Physiography:

Slope: 10 per cent.

Aspect: southeast.

Elevation: 7450 feet.

Geologic formation: basalt (Qtb).

Type of opening: 1-H strip cut simulated by a power line.

Sample design: two parallel transects perpendicular to the edge of timber, each consisting of 45 sample points spaced 1/4-H apart.

The average tree heights and densities of the timber surrounding the opening for each of the study sites are given in Table 1.

Table 1. The average tree heights and densities of the timber surrounding the opening at each of the study sites.

Site	Tree Height (feet)	Timber Density (square feet of basal area per acre)
Vespidae	75	85
Annex	50	93
Hon-dah	50	115
Navopache	50	76
East	45	80
Upper APS	45	155
Lower APS	70	120

At all study sites, the openings were oriented with their long axis up and down the slope.

#### Field Procedures

Two parallel transects, each extending 5-H into the surrounding timber on both sides of the opening, were established at each of the seven study sites. All sample points were located continuously along each transect at an

interval of 1/4-H. The sample design used at all sites is illustrated in Figure 2.

During the snow season of 1972-73, source data were collected at each of the seven study sites on 10 sampling dates. The time interval between sampling dates was usually two weeks. Whenever a sampling expedition was undertaken, it was attempted to measure all study sites on the same day, conditions permitting. Total snow depth and snowpack water equivalent were measured at each sample point with a Federal snowtube and scale.

The actual dates of snowpack measurements are shown in Appendix A.

After every sampling date, the "average" snowpack profile was computed for each study site by averaging each pair of sample points established along the transects. These profiles were then graphed (see Appendix B for those at time of peak accumulation).

### Analytic Procedures

#### Preliminary Analysis

In the summer of 1972, a preliminary analysis was conducted on source data that had been collected at the East Strip Site in the winter season of 1965. This analysis employed the technique of the two-dimensional model described in the Introduction. Average snowpack profiles were developed from data collected for nine measurement

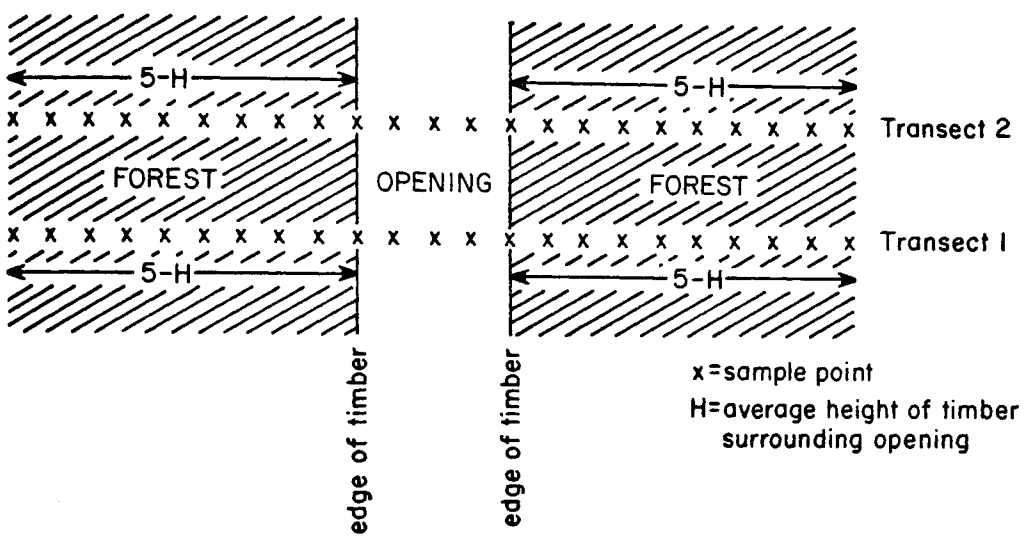


Figure 2. Sample design used at all study sites.

dates in the winter of 1965 (Ffolliott and Hansen, 1968). A "zone of influence" for each profile was delineated by use of the "15 per cent rule," which allows differences of 15 per cent in water equivalent to be attributed to spatial variations in forest overstories and measurement errors. Thus, differences exceeding this value were considered to be due to the influence of the opening. The "zone" itself was bounded by sample points to the windward and leeward of an opening which had measurable, i.e., 15 per cent, differences in snowpack water equivalent as compared to sample points farther from the opening.

Once these "zones" had been delineated, curve fitting procedures were employed to determine the "best" statistical fit of the sampled data points corresponding to the snowpack water equivalent measurements in the "zones of influence." These data points had been previously assigned X,Y coordinates within the Cartesian system, as described in the Introduction. These curves were then integrated to determine the areas above and below the X-axis and the net area was then determined by subtracting the total area below the X-axis from the total area above the X-axis. Thus, the "net" effect of the opening was known at nine different points in time, which corresponded to the nine sampling dates.

The following procedure was used to develop a technique which could predict the "net" effect of an

opening at any point in time. A "net" effect of the East Strip Site opening was determined by the two-dimensional technique for the nine sampling dates throughout the 1965 snow season. Let each of these "net" effects be represented by  $Y_i$ ; thus, there are  $Y_1, Y_2, \dots, Y_9$ . To incorporate time considerations, the change in  $Y_i$  ( $\Delta Y_i$ ) between each set of measurement dates, i.e.,  $Y_2 - Y_1, Y_3 - Y_2$ , etc., was regressed with the change in several independent variables corresponding to the same time period as  $\Delta Y_i$ . The independent variables consisted of those that, theoretically, affected snow accumulation and melt processes but yet were readily obtainable data. A 7072 Multiple Linear Regression was employed utilizing the University of Arizona computer facilities.

The independent variables included in this multiple linear regression analysis were: (1) temperature, (2) precipitation, (3) potential radiation, (4) vapor pressure, (5) albedo, (6) solar declination, and (7) cloud cover. The prime purpose of the preliminary analysis was to determine which of these independent variables were well correlated with  $\Delta Y_i$ , the dependent variable. Once this was known, non-significant variables would not be included in the source data collection for the final study.

The independent variables used in this preliminary analysis were expressed in the following manner,

1. Temperature. The total number of degree-days, i.e., the number of degrees the maximum daily temperature exceeds 32°F, was calculated for each time period between each set of sampling dates. Temperature data were recorded on the Beaver Creek Watershed, within 0.5 miles of the study site.
2. Precipitation. The total amount of precipitation that occurred between each set of sampling dates was expressed in inches of water equivalent. Precipitation data were recorded on the Beaver Creek Watershed.
3. Potential radiation. The total number of langleys incident at the top of the atmosphere between each set of sampling dates was computed (Frank and Lee, 1966).
4. Vapor pressure. Humidity readings taken at Flagstaff, Arizona, approximately 40 miles north of this study area, were converted into vapor pressures, and then the vapor pressure gradients were computed between the snowpack surface and the overlying atmosphere. This variable was expressed as the average vapor pressure gradient that occurred between each set of sampled dates.
5. Albedo. The reflectivity of the snow surface regarding short-wave radiation was developed by determining the number of days between snowfall

events, and then computing the corresponding albedo for each day during the sampled dates interval from appropriate curves (U. S. Army Corps of Engineers, 1956). An average albedo value was used for the interval between sampling dates.

6. Solar declination. The average solar declination during the sampled dates intervals was computed by use of appropriate tables (Smithsonian Meteorological Tables, 1939).
7. Cloud cover. Cloud cover conditions at Flagstaff were recorded. The average cloud cover, expressed as daily per cent coverage, was used for each sampling date interval. Other expressions of cloud cover were also used for the sampling dates intervals. These included total number of completely overcast days during the period, total number of completely clear days during the period, total number of days with "heavy" cloud cover (greater than 70 per cent), and total number of days with "light" cloud cover (less than 30 per cent) during these same time periods.

Results of the preliminary analysis showed that the vapor pressure gradient and cloud cover variables should be omitted from the final study. The non-significance of these variables may have been caused by the extrapolation of these

data from a source 40 miles away from the actual site; on-site conditions may have been different. It was also decided to omit the solar declination variable from the final study because it was highly correlated with the potential radiation variable; also it was not as statistically significant as potential radiation in the regression analysis.

From the preliminary analysis, the variables to be used in the final study that were time dependent and readily available for data collection were determined to be temperature, precipitation, potential radiation, and albedo.

#### Final Analytic Procedures

While utilizing the two-dimensional technique to compute the "net" effect of an opening during the preliminary analysis, two major problems were encountered. The first of these concerned the "zone of influence," or the physical extent of an opening's effect on snowpack conditions. The use of the 15 per cent value to define "measurable differences" was not desirable in that it was too arbitrary a figure. Also, in actual practice, the delineation of the "zone" itself was difficult, stemming from the fact that often a single sample point would exceed the 15 per cent value and, thus, form one boundary of the "zone" while many other sample points supposedly in the "zone of influence" would be well within the 15 per cent

value of the undisturbed (outside of the influence of the opening) forested condition. Further, in many instances, there was such extreme rapid fluctuations ("noise") from one sample point to the next, perceiving the water equivalent of the undisturbed forested condition, i.e., the X-axis in the Cartesian coordinate system, was difficult. In short, too much subjective judgment along with knowledge of the site characteristics and an understanding of the physical processes affecting the snowpack was needed to delineate the "zone of influence."

Secondly, even once the "zone of influence" was delineated and the sample points within it transferred to the Cartesian coordinate system, the "best" statistical fit of these data points using mathematical procedures was often a poor one. Thus, the "net" effect of an opening on a measurement date did not always accurately reflect actual field conditions. It was therefore decided to develop a new technique that would determine the "net" effect of an opening at a given point in time to replace the previously described two-dimensional technique.

It should be understood that the new technique about to be described will be initially used to determine the "net" effect of an opening at a given point in time. Later, the values obtained from the output of this technique will become the dependent variables ( $Y_i$ 's) to be predicted with time considerations.

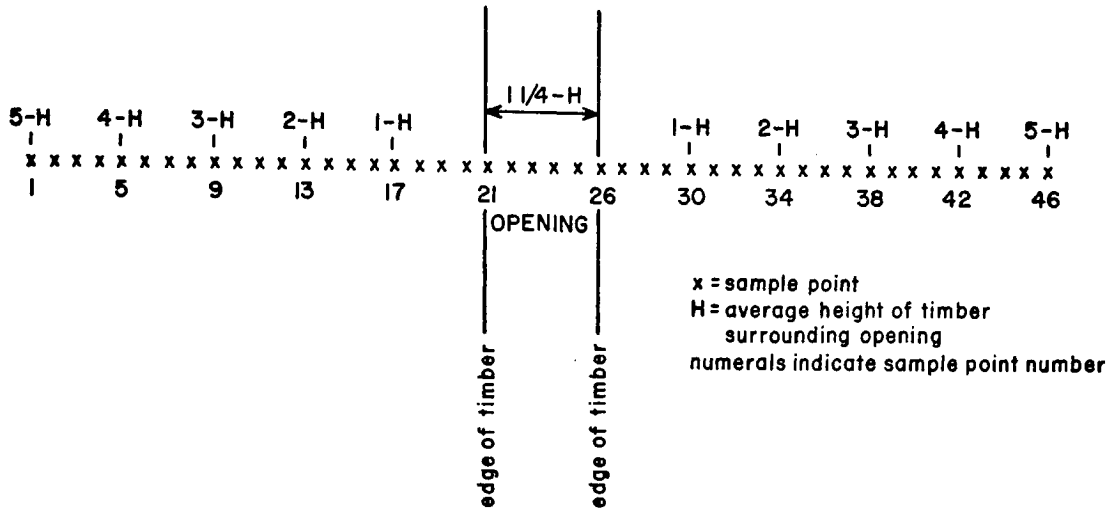
Instead of attempting to delineate a specific "zone of influence" on the average snowpack profile for a sampling date, the assumption was made that the entire influence of an opening is confined somewhere within the boundaries of the measurement transect, which in all cases extended 5-H into the forest from both edges of the simulated strip cuts. This assumption is supported by other studies having demonstrated that the effect of a strip cut is virtually non-existent by the 2- to 3-H point within the forest (Anderson, 1963; Rothacher, 1965; Hansen and Ffolliott, 1968). This assumption alleviated the need of definitively delineating an actual "zone of influence" which in reality may be tenuous because of frequent changes with time; for example, the effect of an opening may extend farther into the forest during a very windy precipitation event than it might under calm melt conditions.

Without a "zone of influence" analysis, there is no need for utilizing a Cartesian coordinate system, which previously used the X-axis to represent the average forested condition. However, the average snowpack water equivalent of the undisturbed forested condition must still be determined in order to evaluate the effect of an opening. It was assumed that as one proceeds deeper and deeper into the forested condition away from an opening, the effect that an opening has on snowpack conditions becomes less and less. Thus, it was felt, and subsequently verified, that the zones

between 3-H and 5-H on both sides of the opening would be most representative of the undisturbed forested condition. However, it also may be possible that the entire influence of the opening at some points in time is confined within the opening itself. If this was the case, the mathematical average of all sample points within the forest would be most representative of the undisturbed forested condition.

Since a strict delineation of the extent of influence into the forest which an opening exerts at any given point in time is difficult, it was felt that a weighted average of all sample points within the forested condition would be the "best" way to determine the average snowpack water equivalent of the undisturbed forested condition. Since it was felt that the 3-H and 5-H zone was most representative of the forested condition at all points in time, the sample points within this zone were given the heaviest weight. As one proceeds closer and closer to the opening, these zones were given less and less weight due to the likelihood that at any point in time, these zones would be more affected by the opening. Thus, those sample points from 3-H to 5-H were given a weight of 4; those from 2 to 2-3/4-H, a weight of 3; those from 1 to 1-3/4-H, a weight of 2; and those from 0 to 3/4-H, a weight of 1. This weighting procedure is illustrated in Figure 3.

This weighted average technique was considered to have a sound theoretical basis along with the advantage of



Distance away from edge of opening	Corresponding sample point numbers	Averaged water equivalent value for these sample points (1) (inches)	Weighting factor (2)	(1)x(2) (inches)
3-H through 5-H	1-9, 38-46	8*	4	32
2-H through 2-3/4-H	10-13, 34-37	5	3	15
1-H through 1-3/4-H	14-17, 30-33	4	2	8
0-H through 3/4-H	18-21, 26-29	3	1	3
			$\Sigma = 10$	Total weight = 58

Total weight  $\div \Sigma$  Weighting factor = 58 inches  $\div$  10 = 5.8 inches = the average water equivalent of the undisturbed forest.

\*These values would be computed from the actual data.

Figure 3. Illustration of the weighting procedure utilized in the study.

being consistent over all sites and all points in time in evaluating the average snowpack water equivalent of the undisturbed forest. The computed average snowpack water equivalents for the undisturbed forested condition using this weighted average technique are given in Appendix C for all seven study sites on each measurement date for the winter season of 1972-73.

Once the average snowpack water equivalent of the undisturbed forested condition has been determined, it is possible to obtain the net effect of the opening in either of two ways:

1. Draw the line representing the average snowpack water equivalent of the undisturbed forested condition through the graphed average snowpack profile that has been developed for the measurement date one is analyzing (see Appendix D). Then, determine the area under the snowpack profile that lies above this line and below it by utilizing a planimeter. Subtract the total area obtained below the line from the total area above the line, the result being the "net" effect of the opening on the measurement date of interest.
2. Mathematically compute the signed deviation between that of the observed water equivalent of every sample point in the average snowpack profile and the average snowpack water equivalent of the undisturbed

forested condition. The summation of these deviations results in the "net" effect of the strip (or other opening) for the point in time one is analyzing.

The latter method was utilized in the analysis of the field data in this study since it was less time consuming. This overall technique for analyzing the opening effect eliminates the need for curve fitting of the data points and, consequently, was felt to more accurately represent actual field conditions. The "net" effects of the openings for each of the seven study sites on each of the 10 measurement dates are given in Appendix E.

The specific objective of this study was to develop a technique which could enable the land manager to predict the "net" effect of an opening as a function of time at any given location. In order to accomplish this, the "net" effect of the opening calculated for the different sites over the snow season period had to be correlated with independent variables that changed with time and other independent variables that changed with differing locations. Thus, the final goal would be a predicting equation into which the input of data concerning the pertinent independent variables would result in the determination of the dependent variable  $y$ , the "net" effect of the opening. The data input

for these pertinent independent variables would depend on the time period of analysis and the location of interest.

From the preliminary analysis, the independent variables that changed with time to be utilized in the development of the final equation were determined to be temperature, precipitation, potential radiation, and albedo. Additionally, pertinent independent variables that changed with location but were independent of time were also needed in order to develop the final desired equation. Unfortunately, the preliminary analysis furnished no information regarding variables that changed with site since the past appropriate source data had been available for only one study site. Therefore, site variables that theoretically affected snow accumulation and melt processes were considered for analysis. These variables were: (1) opening width, (2) timber density, (3) elevation, (4) tree height, and (5) the slope-aspect of the location.

A list describing the development of all the independent variables utilized in the final analytic phase follows. Time dependent variables were:

1. Temperature. The total number of degree-days occurring between each time interval were calculated for each site from temperature records.
2. Potential radiation. Curves were developed for each site from December 1 through May 31 utilizing appropriate values obtained from tables (Frank and

Lee, 1966). Daily potential radiation values were obtained from the developed curves and recorded. The variable was then expressed as the total number of langleys occurring between measurement dates at each site.

3. Precipitation. The precipitation, expressed as inches of water equivalent, that occurred at each site was recorded for each interval between measurement dates.
4. Albedo. By determining the number of days between precipitation events from weather records, the daily snowpack albedo was calculated for each site. These calculations were made by use of changes of albedo with time curves (U. S. Army Corps of Engineers, 1956). The average daily albedo was then computed for each of the time intervals at each of the sites.

Source data for temperature and precipitation records

were:

<u>Site</u>	<u>Closest Meteorological Station</u>	<u>Approximate Distance From Site to Station</u>
East Strip	Happy Jack	0.5 miles
Upper APS	Happy Jack	0.6 miles
Lower APS	Happy Jack	0.6 miles
Vespidae	Castle Creek Experimental Watershed	0.2 miles
Annex	Castle Creek Experimental Watershed	3.3 miles
Hon-dah	McNary	4.0 miles
Navopache	Lakeside	2.0 miles

Site dependent variables were:

1. Opening width. This variable was expressed in terms of the average tree height (H) of the timber surrounding the opening. For example, if opening width is 75 feet, and average tree height is 50 feet, then the opening width is  $1\frac{1}{2}H$ .
2. Timber density. On-site evaluations of the average timber density along the measurement transects on either side of the opening were conducted using a point sampling technique with a basal angle factor of 10. This variable was expressed as square feet of basal area per acre.
3. Elevation. This variable was expressed in feet. The elevations were obtained from U.S.D.I. Geological Survey 7-1/2 minute quadrangle maps.
4. Tree height. The average tree height of the timber surrounding the opening was expressed in feet.
5. Slope-aspect. Using the data previously gathered for potential radiation, the average number of langleys per day that each site received from December 1 through May 31 was computed. This was a way of numerically expressing the slope-aspect combination for different locations and thus did not change with time once computed for a given site. In comparison, the potential radiation variable listed under "Time Dependent Variables" is one that is used

to evaluate the actual potential radiation inputs over a given time period at an individual site.

Thus, a total of nine independent variables, four time dependent and five site dependent, were utilized in the development of the desired equation.

Two methods of correlating the independent variables with the dependent variable were utilized in attempting to develop an equation that would predict the "net" effect of an opening as a function of time at a given location. In both methods, the values of all the independent variables remained the same but the values of the dependent variable differed. In the first method,  $\Delta Y_i$  was computed for each interval between sampling dates, as described in the preliminary analysis. The nine independent variables ( $X_1, X_2, \dots, X_9$ ) were then regressed on these  $\Delta Y_i$ 's by means of a stepwise multiple linear regression using the University of Arizona's computer facilities. In the second method, the actual values of the "net" effect of the opening at the end of each time period, each time period being independent from all others, were used as the values of  $Y_i$ . An example of the methodology of these two regression analyses is given in Table 2.

The data compilation outlined in Table 2 was repeated for each of the study sites. The data compilations from all study sites over all the time periods were then

Table 2. Example of methodology used in the regression analyses

Site	Time period	X <sub>1</sub>	X <sub>2</sub>	X <sub>3</sub>	X <sub>4</sub>	X <sub>5</sub>	X <sub>6</sub>	X <sub>7</sub>	X <sub>8</sub>	X <sub>9</sub>	Case I: Stepwise	Case II: Stepwise
											multiple regression using $\Delta Y_i$ value during stated period (inches of water equivalent)	multiple regression using actual $Y_i$ value at end of stated period (inches of water equivalent)
East	Dec. 21-Jan. 12	9,925	132	.59	3.47	599	80	45	1.75	7,500	4.18	9.23
	Jan. 12-Jan. 27	7,117	117	.64	1.26	a	a	a	a	a	5.05	14.28
	Jan. 27-Feb. 10	7,370	132	.68	0.94						-1.83	12.45
	Feb. 10-Mar. 3	12,860	184	.70	4.08						9.74	22.19
	Mar. 3-Mar. 17	9,824	34	.75	5.50						-9.20	12.49
	Mar. 17-Mar. 31	10,863	108	.73	5.05						2.76	15.75
	Mar. 31-Apr. 17	14,418	261	.66	1.49						25.52	41.27
	Apr. 17-Apr. 28	9,931	149	.62	0.58						-13.42	27.85
	Apr. 28-May 12	13,207	306	.64	0.93						-13.50	14.35

where:  
X<sub>1</sub> = Potential radiation (langley).  
X<sub>2</sub> = Temperature (degree-days).  
X<sub>3</sub> = Albedo.  
X<sub>4</sub> = Precipitation (inches of water equivalent).  
X<sub>5</sub> = Slope Aspect (expressed as average daily langleys).  
X<sub>6</sub> = Density of timber (square feet of basal area per acre).  
X<sub>7</sub> = Tree height (feet).  
X<sub>8</sub> = Elevation (feet).  
X<sub>9</sub> = Opening width (expressed in terms of H).

<sup>a</sup>These variables do not change at a given site.

included in each of the two stepwise multiple regression analyses. Each analysis consisted of a total of 63 sets of data points, i.e., dependent variable with corresponding independent variables.

If both of these methods produced equally "good" predictive equations, it was assumed that the method utilizing the actual "net" opening effect at the end of the desired time period would be most useful to the land manager. A  $\Delta Y_1$  predicted value by the equation would furnish information only as to the change in the "net" effect of the opening that had taken place. However, the other method would directly yield the actual "net" effect of the opening at the point of time of interest.

## RESULTS AND DISCUSSION

For each of the two methods of expressing the dependent variable discussed in the Analytic Procedures section, a separate regression analysis was conducted. As previously mentioned, this analysis consisted of a stepwise multiple regression being performed on each of the two complete sets of data; one set using  $\Delta Y_i$  as the dependent variable, the other set using  $Y_i$  at the end of each time period as the dependent variable. A restraint incorporated into the computer program would not allow an independent variable to enter in the stepwise analysis if the F-ratio of the entering variable fell below 1.25. Thus, whenever this situation arose, the stepwise regression was terminated.

Each regression analysis consisted of five separate runs, each run utilizing varying combinations and expressions of the independent variables. The specific combinations are shown below.

	<u>Method 1</u>	<u>Method 2</u>
Run 1	$\Delta Y_i$ vs. all linear independent variables $(X_1, X_2, \dots, X_9)$	$Y_i$ vs. same as Method 1
Run 2	$\Delta Y_i$ vs. all linear independent variables and all squares of these variables $(X_1^2, X_2^2, \dots, X_9^2)$	$Y_i$ vs. same as Method 1

	<u>Method 1</u>	<u>Method 2</u>
Run 3	$\Delta Y_i$ vs. all linear independent variables, squares of these same variables, and some of their cross-products ( $X_1X_2, X_1X_3, X_1X_4, \dots, X_1X_9; X_2X_3, X_2X_4, \dots, X_2X_9; X_3X_4, X_3X_5, \dots, X_3X_9;$ and $X_4X_5, X_4X_6, \dots, X_4X_9$ )	$Y_i$ vs. same as Method 1
Run 4	$\Delta Y_i$ vs. all linear independent variables, squares of these same variables, and the remaining cross-products omitted in Run 3 ( $X_5X_6, X_5X_7, \dots, X_5X_9; X_6X_7, X_6X_8, X_6X_9, X_7X_8, X_7X_9,$ and $X_8X_9$ )	$Y_i$ vs. same as Method 1
Run 5	$\Delta Y_i$ vs. all linear independent variables, squares of those same variables, and ratios of these variables	$Y_i$ vs. same as Method 1

It had been previously decided that, if the stepwise analysis for a given run exceeded three steps before termination, those equations beyond Step 3 would not contribute variables that were of "real" significance in predicting power. It was felt that after Step 3 the regression analysis essentially would become a curve-fitting procedure rather than providing additional significant terms for predictive purposes. Admittedly, this assumption is more of an opinion than fact; therefore, results of the analyses are given through Step 5 in all cases of significant regression analyses. Also, the termination point of each of the significant regression analyses along with the final equation's

F-Ratio,  $R^2$  value, and standard error are given for each run.

There were no significant regressions at the  $\alpha = .01$  level utilizing method 1, i.e., the dependent variable expressed as  $\Delta Y_i$ . Therefore, the equations presented in Table 3 express  $Y_i$  as the "net" effect of the opening at the end of each of the time intervals between measurement dates, all time periods being independent of one another. All equations presented are significant at the  $\alpha = .01$  level.

Certain inferences were made by studying the significant equations presented in Table 3. It was apparent that certain variables, either in their linear form, squared form, or as a term in a crossproduct, consistently appeared in all the significant equations through Step 3. As previously explained, it was felt that variables present through Step 3 in significant equations would be of "real" significance in either directly affecting the processes contributing to the "net" effect of an opening or being indirectly representative of these processes. Thus, in this example of the technique, the significant variables well correlated with the "net" effect of an opening and, therefore, those that would be used for predictive purposes were: (1) timber density surrounding the opening ( $X_6$ ), (2) opening width ( $X_9$ ), (3) precipitation ( $X_4$ ), and (4) slope-aspect ( $X_5$ ).

Table 3. Significant equations developed in the study.

Run	Step	Significant equations	F-Ratio	R <sup>2</sup>	Standard error (inches)	Comment
Run 1		No equations significant at $\alpha = .01$ level				
Run 2	Step 1	$Y = 16.5 - .000968X_6^2$	11.1	.176	12.9	This run terminated after Step 5.
	Step 2	$Y = 44.7 - .00154X_6^2 - 8.02X_9^2$	17.1	.402	11.1	
	Step 3	$Y = 40.7 - .00167X_6^2 - 7.42X_9^2 + .513X_4^2$	17.5	.512	10.1	
	Step 4	$Y = 118 - .00152X_6^2 - 9.06X_9^2 + .450X_4^2 - .113X_5$	16.7	.577	9.51	
	Step 5	$Y = 346 - .00102X_6^2 + 53.1X_9^2 + .389X_4^2 - .260X_5 - 189X_9$	17.4	.645	8.81	
Run 3	Step 1	Same as Run 2	11.1	.176	12.9	Terminates at end of Step 6: F-Ratio = 23.2, R <sup>2</sup> = .748, and standard error = 7.51.
	Step 2	Same as Run 2	17.1	.402	11.1	
	Step 3	$Y = 41.4 - .00197X_6^2 - 7.49X_9^2 + .0281X_4X_6$	19.0	.533	9.90	
	Step 4	$Y = 122 - .00180X_6^2 - 9.18X_9^2 + .0261X_4X_6 - .119X_5$	18.9	.607	9.17	
	Step 5	$Y = 358 - .00127X_6^2 + 55.3X_9^2 + .0243X_4X_6 - .270X_5 - 196X_9$	20.5	.681	8.36	
Run 4	Step 1	$Y = 39.9 - .211X_6X_9$	29.6	.362	11.3	Terminates after Step 1; F-Ratio = 19.3, R <sup>2</sup> = .746, and standard error = 7.61.
	Step 2	$Y = 37.4 - .218X_6X_9 + .479X_4^2$	22.1	.464	10.5	
	Step 3	$Y = 117 - .226X_6X_9 + .471X_4^2 - .119X_5$	21.3	.561	9.60	
	Step 4	$Y = 156 - .289X_6X_9 + .660X_4^2 - .170X_5 + .560X_4X_6$	19.8	.618	9.05	
	Step 5	$Y = 225 - .312X_6X_9 - .570X_4^2 - .297X_5 + .047X_4X_6 + .00342X_6X_7$	18.1	.654	8.70	
Run 5	Step 1	Same as Run 2	11.1	.176	12.9	Terminates after Step 5.
	Step 2	Same as Run 2	17.1	.402	11.1	
	Step 3	Same as Run 2	17.5	.512	10.1	
	Step 4	$Y = 29.9 - .00187X_6^2 - 9.02X_9^2 + .482X_4^2 + .124X_8/X_7$	15.0	.550	9.82	
	Step 5	$Y = -63.6 - .00853X_6^2 - 8.82X_9^2 + .478X_4^2 + .197X_8/X_7 + 1.53X_6$	15.6	.619	9.12	

where:

- $X_1$  = Potential radiation.  
 $X_2$  = Temperature.  
 $X_3$  = Albedo.  
 $X_4$  = Precipitation.  
 $X_5$  = Slope-aspect.  
 $X_6$  = Timber density.  
 $X_7$  = Tree height.  
 $X_8$  = Elevation.  
 $X_9$  = Opening width.

Also, it was observed that in all equations through Step 3, the signs of the coefficients of these variables did not change. Thus, if a land manager had to make a decision concerning the location of a proposed timber cut, and water yield was an important consideration, the above site variables and their coefficients would be of importance since the "net" effect of the opening created by the timber cutting represents the magnitude of on-site snowpack water equivalent. Since these site variables and their coefficients can give information concerning the maximization or minimization of the "net" effect of an opening, the land manager could decide on the site location of a timber cut based on what objective was desired, i.e., maximizing or minimizing the "net" effect of the opening created by the timber cutting, depending on which was desired in a given land management situation.

Since the opening width variable ( $X_9$ ) consistently has a negative coefficient, it is inferred that to maximize the "net" effect of an opening, the width of the opening should be minimized; conversely, opening width should be increased if one wanted to minimize the "net" effect of the timber cutting.

The timber density variable ( $X_6$ ) also has a consistent negative coefficient. Thus, to maximize the "net" effect of an opening created by timber cutting, a site would be chosen with a low density of timber surrounding the cut;

to minimize the "net" effect, high timber densities would be desirable.

The slope-aspect variable ( $X_5$ ) also has a negative coefficient. Therefore, it is inferred that sites with low potential radiation inputs would maximize the "net" effect of an opening created by timber cutting, while those sites with high potential radiation inputs would tend to minimize the "net" effect.

It must be emphasized that these above inferences are drawn only from the range of conditions in the study, and can not necessarily be extrapolated beyond these ranges. Also, the variables found to be of importance and the information concerning their coefficients would not necessarily apply to other areas. These inferences are designed to give an example of the type of information that might be gained by using this technique at any area. The inferences made in this example were for each significant independent variable separately while holding all the other significant independent variables constant. The range of conditions in this study is presented in Table 4.

Thus, when discussing that minimizing timber density results in maximizing the "net" effect of the opening created by timber cutting, this is not to say that a timber density of zero would result in the greatest maximization of on-site snowpack water equivalent. Rather, the discussion is intended to be within the confines of the densities given

Table 4. Range of conditions utilized in the study.

Variable	Units	Range of conditions within study		
		Minimum	Mean	Maximum
Timber Density	Square feet of basal area per acre	76	103	155
Opening Width	H (average height of timber surrounding opening)	1.0	1.6	2.0
Slope-Aspect	Langleys (average input per day between December 1-May 31)	599	658	709

in Table 4. This holds true for the discussion of the opening width and slope-aspect variables, also.

Of the four significant variables found through Step 3 in the significant equations, it was interesting to note that only one of these variables, precipitation, was time dependent. Since 3 out of 4 of the significant variables were a function of site location, it was inferred that differences in the "net" effect of an opening created by timber cutting were greater between the sites studied than were those that occurred within a site over time. Thus, the technique developed provided much information regarding the "net" effect of an opening as a function of its location in this example. Also, since a time dependent

variable was present in the significant equations, it is also possible to predict the "net" effect of the opening as a function of time at any given site.

If the specific results developed in this study were to be used in actual practice, the "best" equation of those given in Table 4 would be selected. This would be the equation given in Run 4, Step 3, since this equation has the highest  $R^2$  value (.561) and the lowest standard error (9.60 inches) of all the significant equations through the Step 3 level. This equation is:

$$Y = 117 - .226X_6X_9 + .471X_4^2 - .119X_5$$

where: Y is the "net" effect of the opening expressed as inches of snowpack water equivalent.

$X_6X_9$  is the timber density-opening width cross-product.

$X_4$  is the precipitation variable.

$X_5$  is the slope-aspect variable.

Information contained in the above equation is two-fold. First, if the land manager wanted to maximize the "net" effect of an opening, he would select a site where  $X_6X_9$  (timber density x strip width) and  $X_5$  (slope-aspect) were minimized within the range of conditions studied. Secondly, having selected the site, if the land manager wanted to predict the "net" effect of such an opening at any point in time, he would evaluate the amount of

precipitation, expressed as inches of snowpack water equivalent, that had occurred within a specified time period and substitute this value for  $X_4$  in the above equation along with the appropriate values for the site variables to determine Y.

Overall, it can be inferred from this "best" equation that a maximum "net" effect of an opening created by timber cutting for the range of conditions studied in Arizona is obtained when a 1-H diameter opening is cut within a low surrounding timber density on a site with low potential radiation inputs during the winter season and receiving high amounts of precipitation. I have developed a theory that attempts to give a logical, physical basis that explains why this combination of variables would result in a maximum "net" effect of the opening.

The opening width variable is of primary importance during snowpack accumulation stages. Narrow opening widths have been shown as early as the 1900's (Church, 1912) to be most effective as snow "traps." The amount of precipitation received affects the magnitude of this opening trapping effect. It is assumed that the greater the amount of precipitation occurring, the larger the trapping effect will become. As time progresses through the snow season, melt processes become of increasing importance in determining the snowpack profile. It is important to realize that in determining the "net" effect of an opening, one is always

comparing the average water equivalent of the snowpack lying within the sphere of influence of the opening with that of the undisturbed forested condition. Thus, at a point in time immediately after a heavy precipitation event, this "net" effect of the opening may be of a large magnitude. However, if melt processes are more active in the opening where this excess accumulation has taken place than those in the forested condition, the "net" effect of the opening will be rapidly diminished during these melt phases. Also, the time distribution of the precipitation events occurring in a winter season may be important in determining the magnitude of the "net" effect of an opening at a given time, i.e., 10 storms each consisting of one inch of water equivalent may be of a different magnitude than one event yielding 10 inches of water equivalent.

It is well documented (Anderson, 1967; Ffolliott and Hansen, 1968) that sites having low potential radiation inputs, i.e., "cool sites," have less intense melt characteristics than do those with high inputs. Therefore, the potential radiation variable is of importance when determining the "net" effect of an opening. Since melt is not so intense on "cool" sites, the opening is not subjected to the ablation present at warm sites. Thus, the differential melting between the opening's sphere of influence and that of the undisturbed forested condition is less on "cool"

sites, resulting in a maximization of the "net" opening effect.

Timber density also has a large effect on the melt characteristics at a given site. It was previously shown that the same trees present on site affect several processes simultaneously (Anderson, 1967). The density of timber determines the amount of short-wave radiation directly impinging on the underlying snowpack. Also, the timber density determines the amount of short-wave radiation that is absorbed and reradiated as long-wave radiation (Reifsnyder and Lull, 1965). Further, wind movement through the forest and, consequently, the amount of evaporation is affected by the same trees present. If the timber surrounding an opening created by timber cutting is dense at a given site, the undisturbed forested condition will ablate at a slower rate than the snowpack within the influence of the opening due to the following reasons:

1. The undisturbed forested condition is heavily shaded resulting in less impingement of direct solar radiation and, consequently, slow melt.
2. The dense timber results in less wind movement, thereby reducing evaporation rates.
3. The snow in the opening is subjected to comparatively large amounts of long-wave radiation from the dense timber surrounding the opening resulting in

accelerated melting along these timber edges. This phenomena is sometimes referred to as "back radiation."

Thus, openings cut in very dense forested areas result in comparatively large differential melting between the undisturbed forested condition and the sphere of influence of the opening. Therefore, previous gains in the "net" effect of the opening made during accumulation phases may be rapidly offset during periods of active melting.

In contrast, rates of melt in the undisturbed forested condition progressively approach those of the opening as the timber density is reduced for the following reasons:

1. The undisturbed forested condition becomes increasingly open to both incoming solar radiation and wind movement resulting in higher rates of ablation.
2. There are fewer trees present around the edge of the opening resulting in a comparatively lower magnitude of "back radiation."

Thus, the low density timber results in a comparatively lower melt rate differential between the undisturbed forested condition and the area of an opening's influence. Therefore, gains made in the "net" effect of an opening

during snowpack accumulation phases are more likely to persist during periods of active melt.

The entire previous discussion has been an attempt to give a physical basis for the combination of variables present in the final equation selected for analysis. It is a theory based on personal field observations and opinions and should be interpreted in this light. Also, it applies only to the range of conditions in Arizona analyzed in this study.

Since the objective of this study was to develop a technique which could enable the land manager to predict the net effect of an opening at any point in time at any given location, a brief summary of the technique is given below:

1. Select several sites which include the range of conditions of interest to the particular land management situation.
2. Take snow measurements at various points in time throughout the snow season at each site using the methods described herein. All measurement transects should extend 5-H into the forest surrounding the opening.
3. Develop an average snowpack profile for each site on each measurement date.
4. Analyze each average profile using the weighted average procedure to determine the average snowpack water equivalent of the undisturbed forested

condition and the subsequent mathematical analysis (both described in Analytic Procedures) to determine the "net" effect of the opening on each measurement date at each site.

5. Select independent variables which either theoretically or from field experience are thought to be of possible significance to the snowpack dynamics in the area of interest. These variables must be readily obtainable. Collect source data for the independent variables selected for each time interval between measurement dates at each site, each time interval being independent of all others.
6. Use multiple regression analysis to empirically correlate the data collected concerning the independent variables with the "net" effect of the opening at the end of each time interval.
7. Select the "best" significant equation to be utilized for predictive purposes by appropriate statistical evaluation.

Once the "best" equation has been selected, the independent variable data collection alone will determine the "net" effect of an opening in subsequent years by making use of this equation. However, it must be emphasized that the "best" equation developed has a certain statistical range of "confidence limits" for predictive purposes.

Therefore, anyone utilizing the above technique must determine whether these "confidence limits" for the equation they have developed are acceptable for their desired "accuracy" of the prediction.

The only method to actually determine the "accuracy" of any prediction equation is to test it by utilizing data from subsequent years. In this study, time has not permitted such a validation of the prediction equation developed. Perhaps further study could provide such a validation.

Throughout this thesis, several values have been given which express the "net" effect of an opening in a forest at a given point in time. These values represent the total inches of snowpack water equivalent present on-site due to the "net" effect of the opening. These values, in themselves, have no physical meaning. To express the "net" effect of an opening in a meaningful manner, space considerations referring to the expression "on-site" must be included. The "net" effect was calculated by summing the signed deviations between the value for the average snowpack water equivalent of the undisturbed forested condition and the water equivalent of each sample point. The following calculation gives the two-dimensional representation of this value.

$$\text{inch-feet} = (\text{Summation of signed deviations in inches}) \\ (\text{interval length between sample points in feet})$$

Since this two-dimensional representation also has little physical meaning, the final expression of the "net" effect of an opening is calculated in terms of volume. To determine the volume of on-site water equivalent represented by the "net" effect, the length of the opening must be incorporated into the calculation. Thus,

$$\text{inch-feet}^2 = \frac{\text{(Summation of signed deviations, inches)}}{\text{(sample point interval length, feet)}} \times \text{(length of strip, feet)}$$

The above defined expression is indeed a volume term but is still rather unwieldy. A much more common expression of volume to the land manager is that of acre-inches. One acre-inch is equal to the depth of one inch of water on a one acre area. The calculation to convert inch-feet<sup>2</sup> to acre-inches is given below:

$$\text{acre-inches} = (\text{inch-feet}^2) \left( \frac{1 \text{ acre}}{43,560 \text{ feet}^2} \right)$$

Since opening lengths varied from site to site in this study, all lengths were assumed to be 300 feet long. This was done to put all numerical figures on the same basis. However, when using this technique to determine the on-site snowpack water equivalent volume present caused by the "net" opening effects elsewhere, the actual length of the opening should be used.

An example of the above-described volume calculation for the "net" opening effect at the Lower APS site on February 10, 1973, is given below:

1. Summation of signed deviations = 9.45 inches.
2. Interval length between sample points = 17.5 feet.
3. Length of strop = 300 feet.

Therefore:

$$9.45 \text{ in} \times 17.5 \text{ ft} \times 300 \text{ ft} \times \frac{1 \text{ acre}}{43,560 \text{ ft}^2}$$

$$= 1.14 \text{ acre-inches.}$$

Table 5 gives the interval length between sample points for each site studied.

Table 5. Interval length between sample points at each site studied.

Site	Interval length between sample points (feet)
East strip	11.25
Lower APS	17.50
Upper APS	11.25
Vespidae	18.75
Annex	12.50
Hon-dah	12.50
Navopache	12.50

Since many readers of this thesis may desire a metric equivalent of all values enumerated herein, a conversion table for all units used in this thesis is presented in Appendix F.

## CONCLUSIONS

The technique developed, as outlined in the Results and Discussion Section, to determine or predict the "net" effect of an opening on the snowpack regime at any point in time at any given location is a viable one. This is evidenced by the resulting significant (at  $\alpha = .01$  level) equations developed from this study (intended to be an illustrative example of the technique) using data collected on seven study sites in the ponderosa pine type of Arizona between December 1, 1972 and May 31, 1973.

The utilization of the technique on the data collected for this study resulted in significant equations from which two types of information could be gathered.

1. Depending on the land manager's objective, the "net" effect of an opening in the forest on the snowpack water equivalent could be either maximized or minimized by selecting appropriate values of the site variables, previously discussed in the Results and Discussion Section, when the location of a proposed timber cut is to be determined.
2. At any given site, the "net" effect of an opening created by timber cutting can be predicted at any point in time in future winter seasons by using the "best" equation developed by the technique.

These same types of information might be yielded by use of the developed technique for locations outside Arizona. The use of the technique in analyzing the Arizona source data demonstrated that changes in the "net" effect of openings were greater between sites studied than were changes occurring over time within a given site.

Further study is needed to validate the equations developed for the Arizona ponderosa pine type in this study regarding their predictive "accuracy," and whether the manipulation of the site variables discussed in the Results and Discussion Section would indeed result in the maximization or minimization of the "net" effect of an opening within the range of conditions studied.

Any actual use of equations developed by utilizing this technique in other locations should first be predicated on discerning acceptable values for "confidence limits" to be used for prediction purposes, and on the validation of the manipulation of site variables in determining locations of proposed timber cuts.

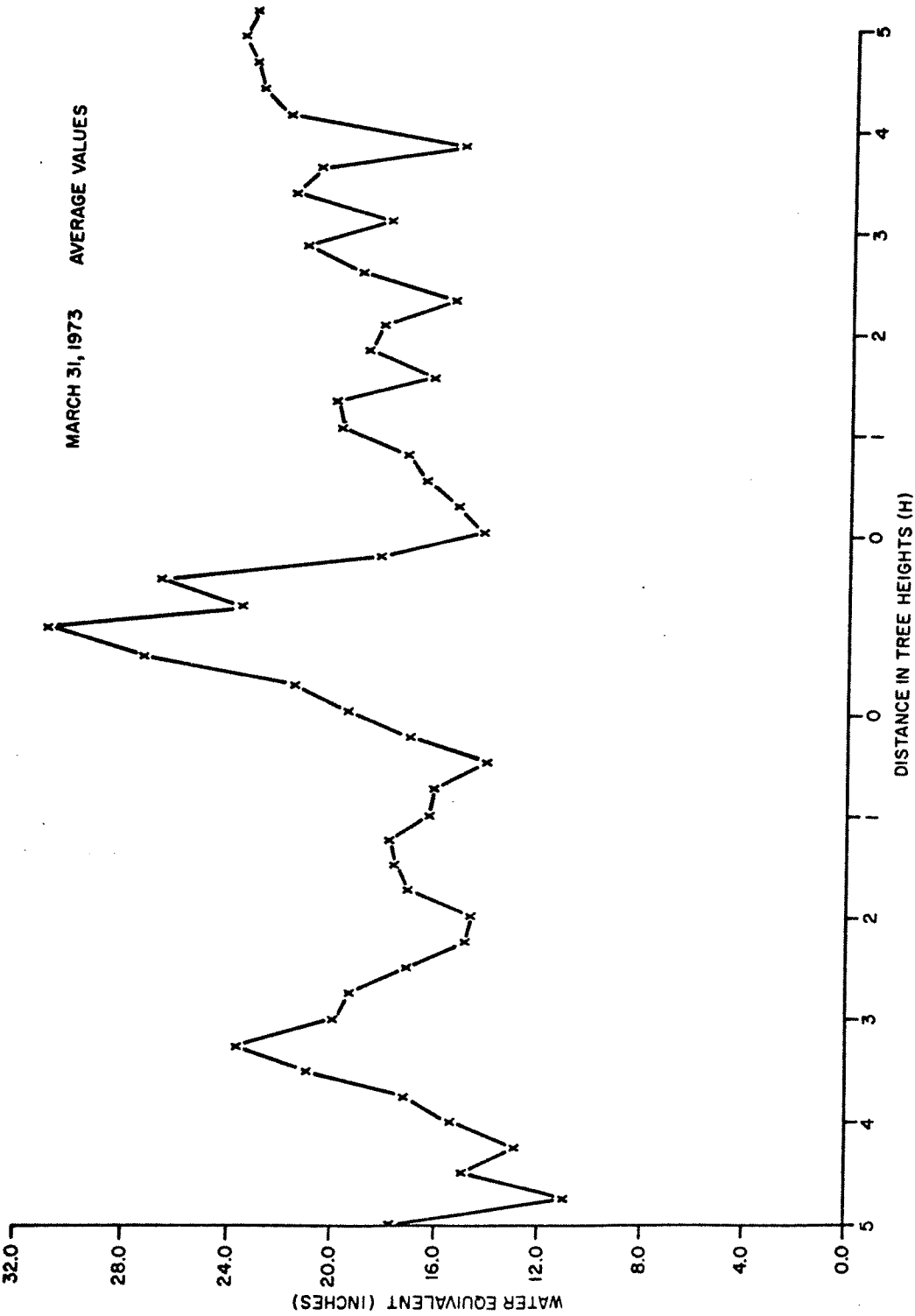
APPENDIX A

THE DATES OF SNOWPACK MEASUREMENT FOR EACH  
SITE IN THE STUDY

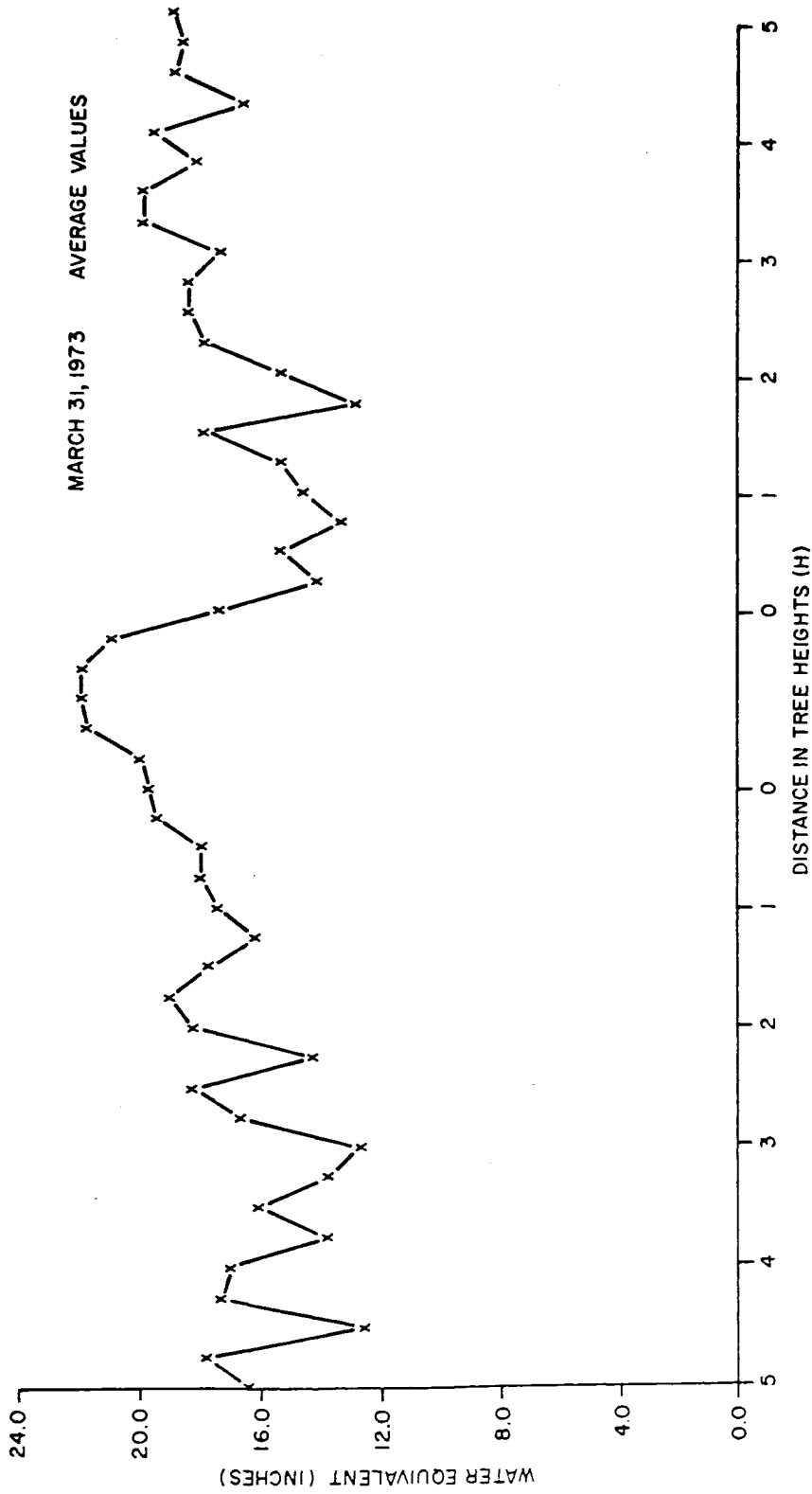
Sampling Date #	Vespidae	Annex	Hon-dah	Navopache	East	Upper APS	Lower APS
1	Dec. 23	Dec. 23	Dec. 23	Dec. 23	Dec. 21	Dec. 22	Dec. 22
2	Jan. 10	Jan. 10	Jan. 11	Jan. 11	Jan. 12	Jan. 12	Jan. 12
3	Jan. 27	Jan. 27	Jan. 27	Jan. 27	Jan. 27	Jan. 27	Jan. 27
4	Feb. 10	Feb. 10	Feb. 9	Feb. 9	Feb. 10	Feb. 10	Feb. 10
5	Mar. 3	Mar. 3	Mar. 3	Mar. 4	Mar. 3	Mar. 3	Mar. 3
6	Mar. 17	Mar. 17	Mar. 17	Mar. 17	Mar. 17	Mar. 17	Mar. 17
7	Mar. 31	Mar. 31	Mar. 31	Mar. 31	Mar. 31	Mar. 31	Mar. 31
8	Apr. 14	Apr. 14	Apr. 14	Apr. 14	Apr. 17	Apr. 17	Apr. 16
9	Apr. 28	Apr. 28	Apr. 29	Apr. 28	Apr. 28	Apr. 28	Apr. 28
10	May 12	May 12	May 12	May 12	May 12	May 12	May 12

APPENDIX B

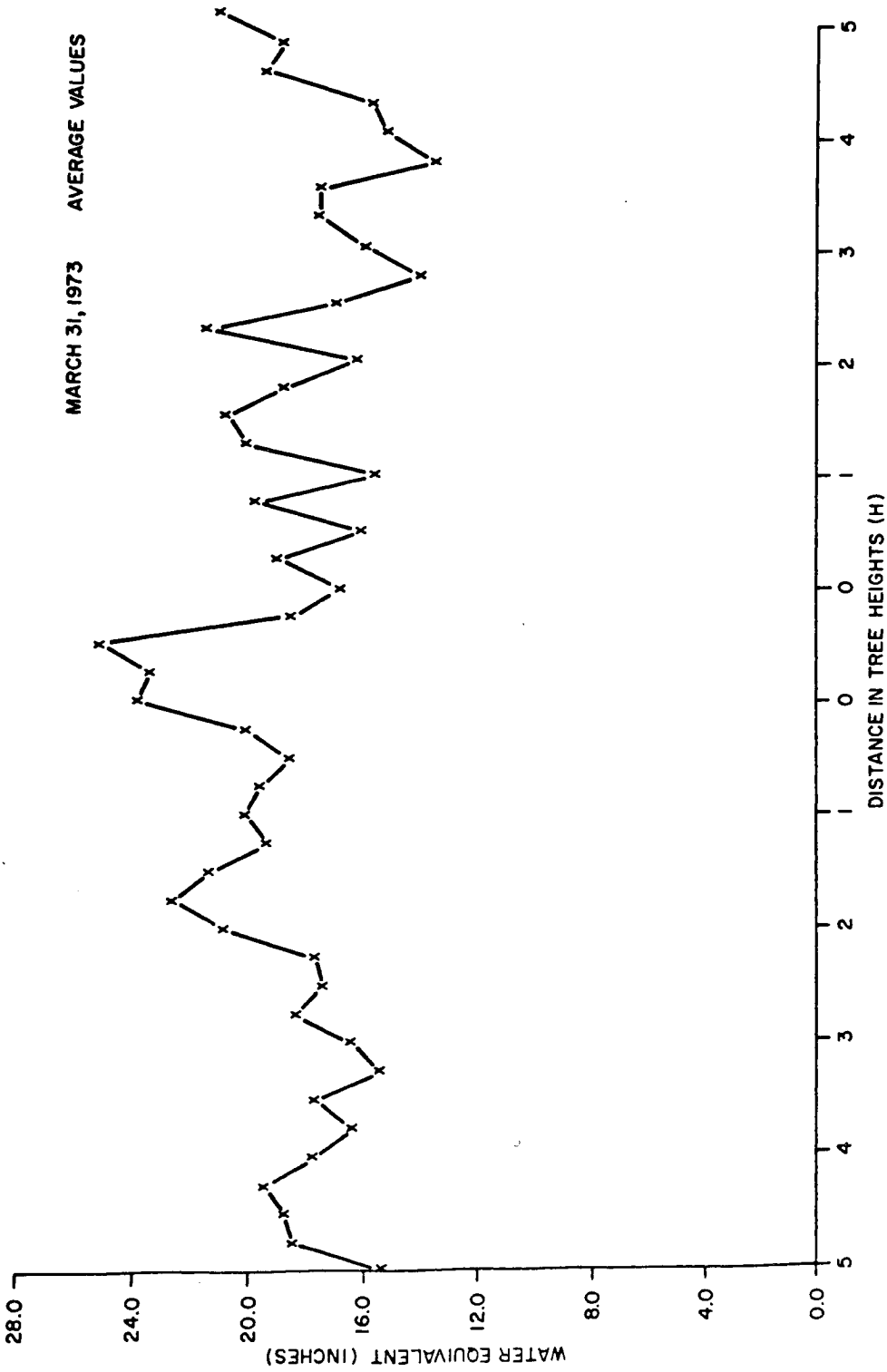
AVERAGE SNOWPACK PROFILES FOR EACH SITE  
AT PEAK ACCUMULATION



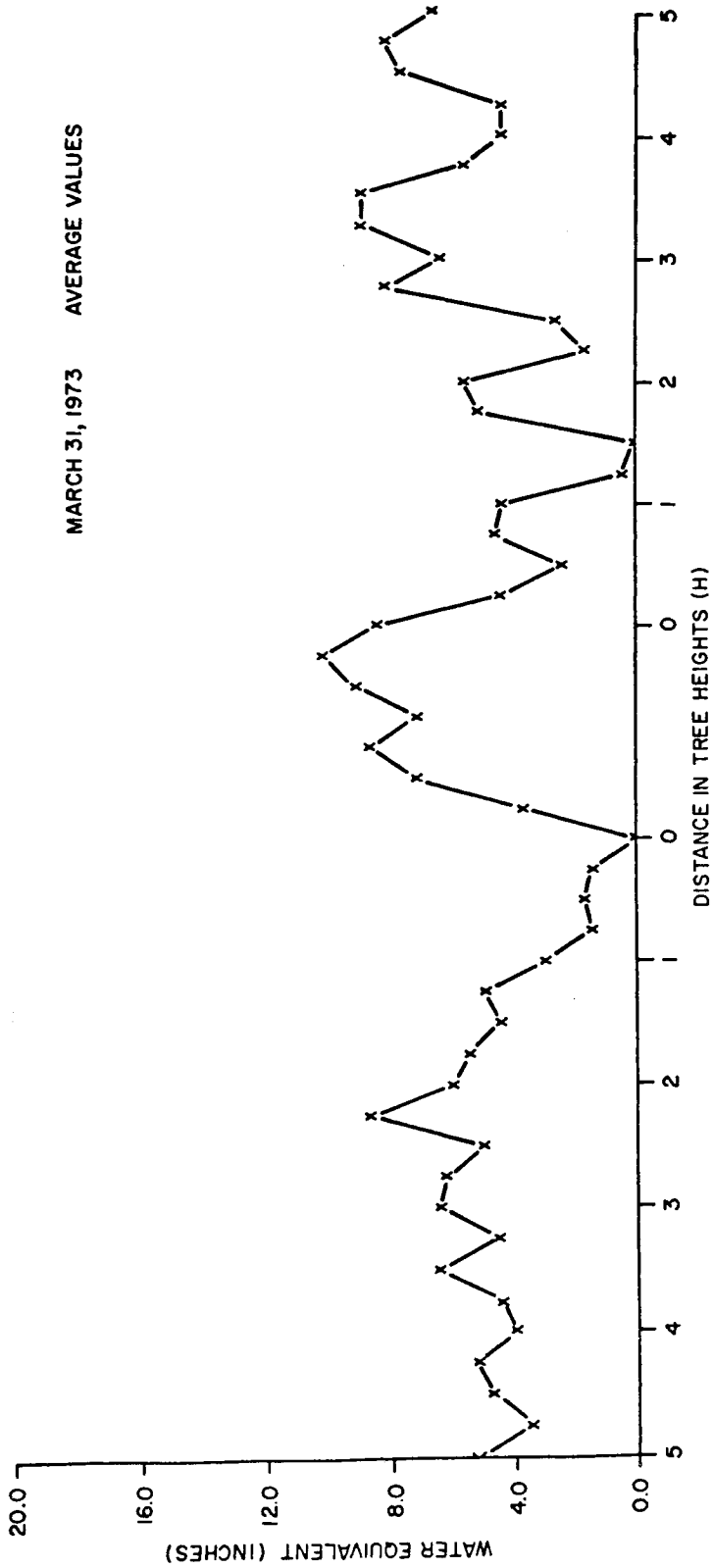
East Strip Site at peak accumulation measurement date



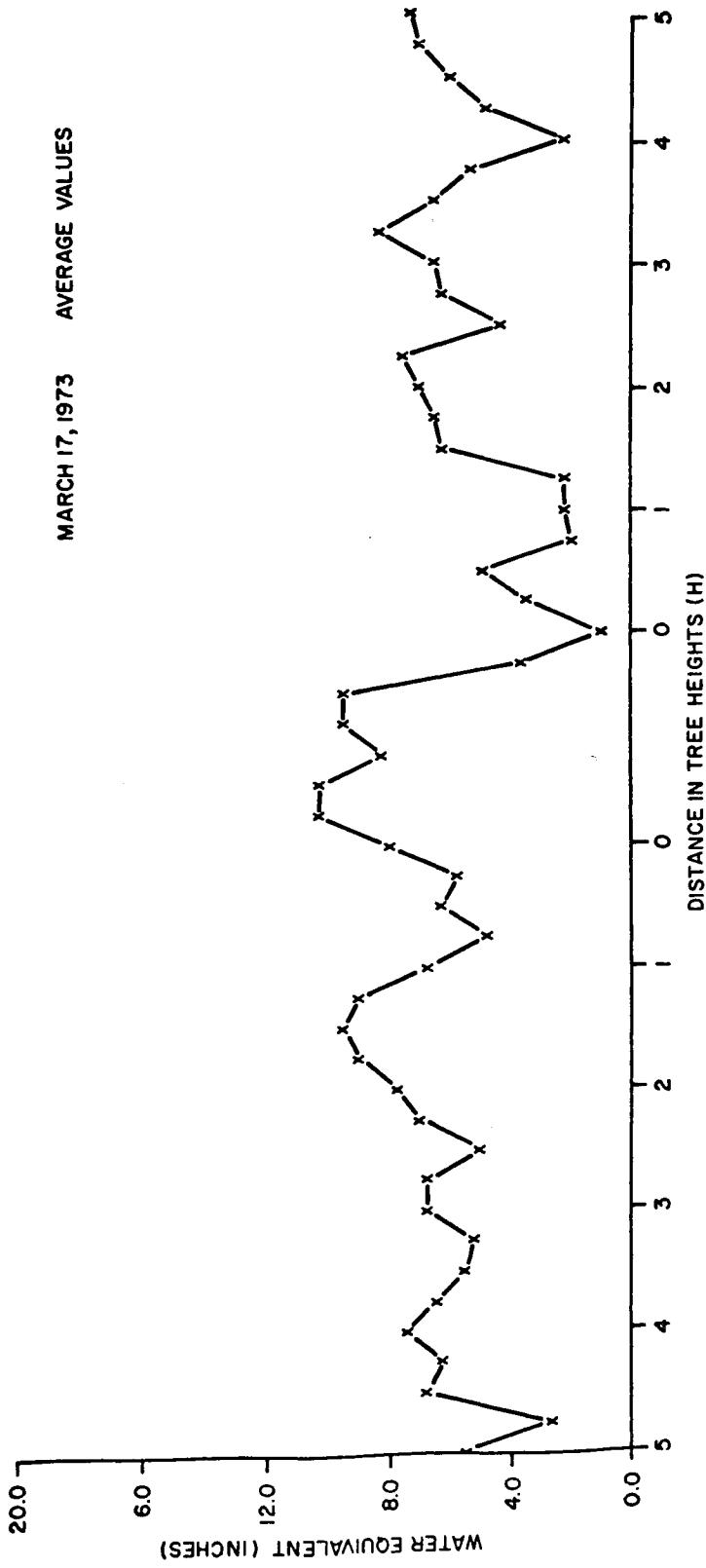
Upper APS Site at peak accumulation measurement date



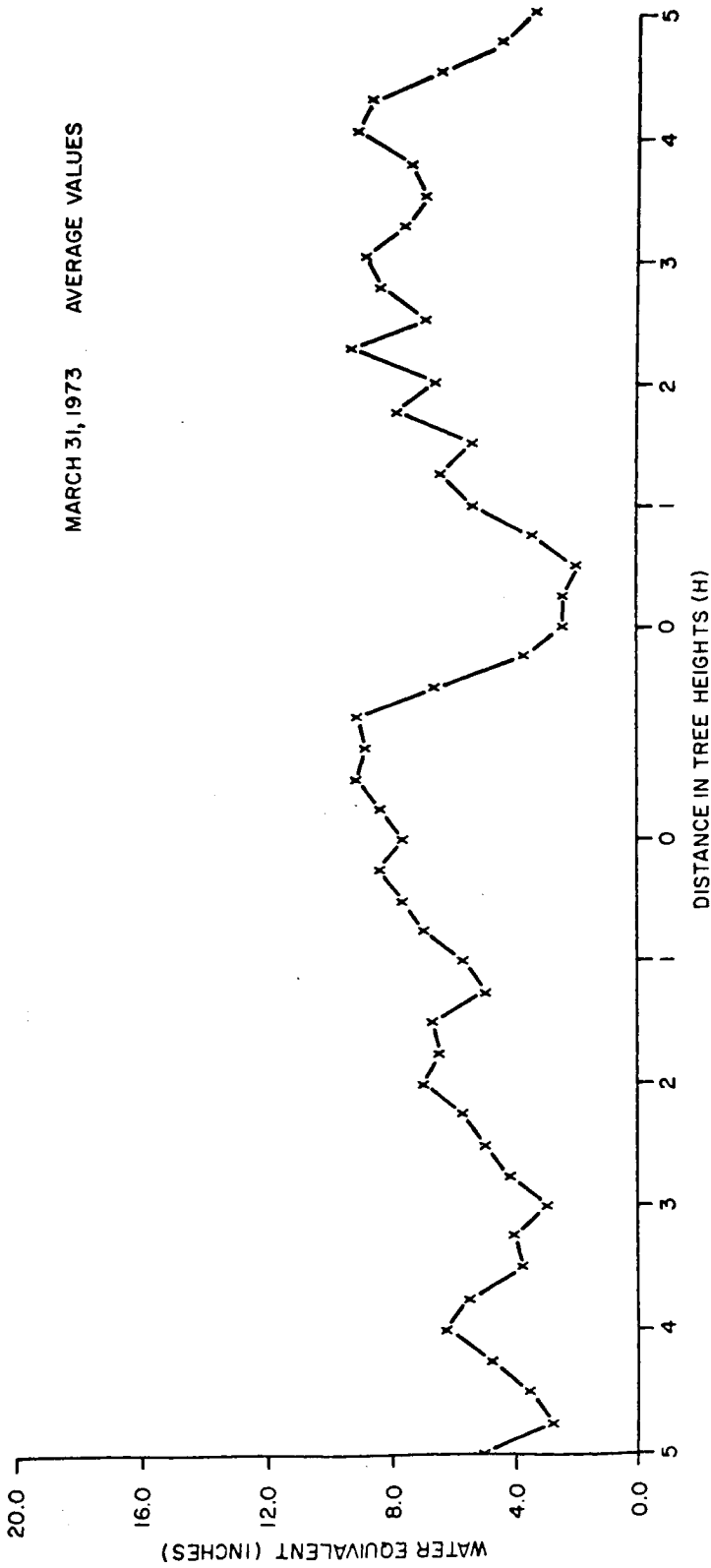
Lower APS Site at peak accumulation measurement date



Vespidae Site at peak accumulation measurement date

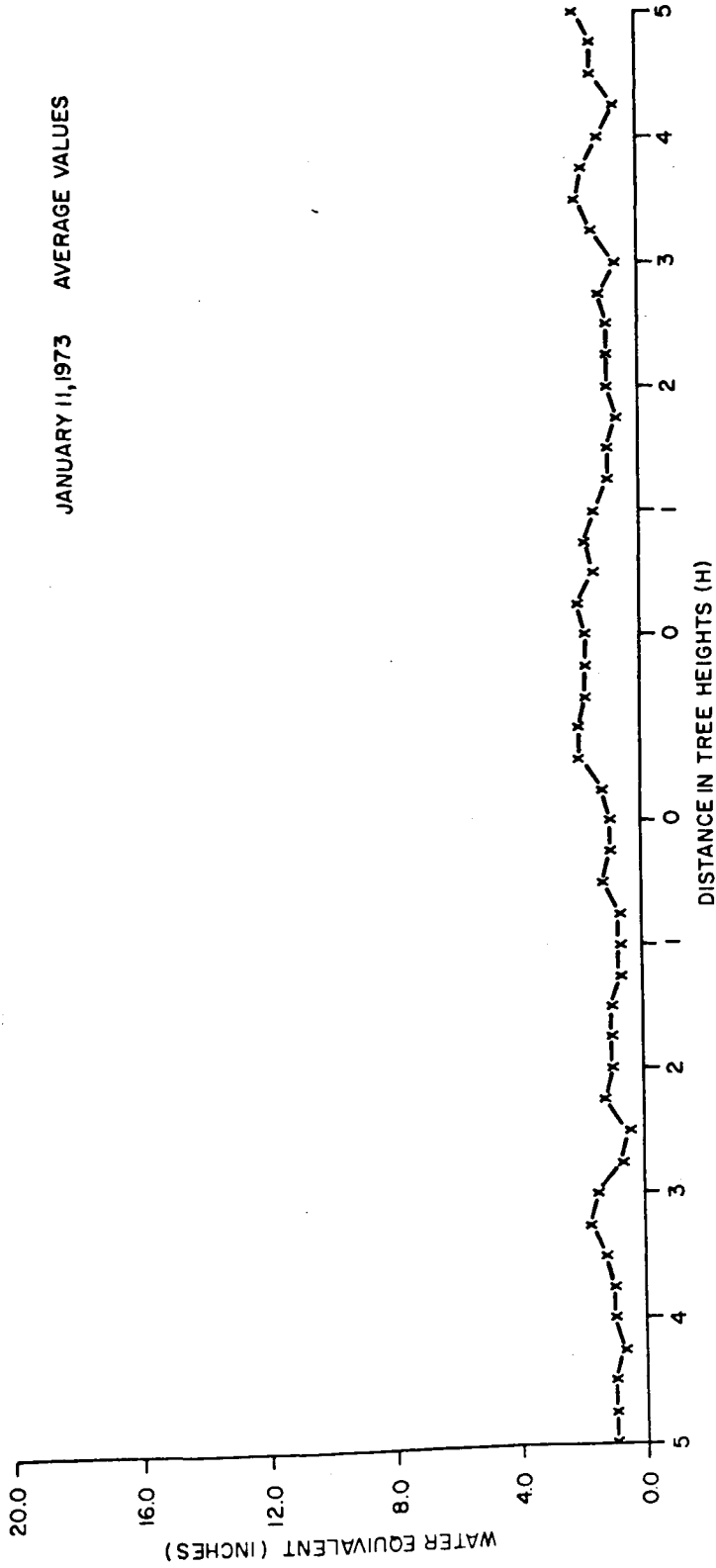


Annex Site at peak accumulation measurement date



Hon-dah Site at peak accumulation measurement date

JANUARY 11, 1973 AVERAGE VALUES



Navopache Site at peak accumulation measurement date

APPENDIX C

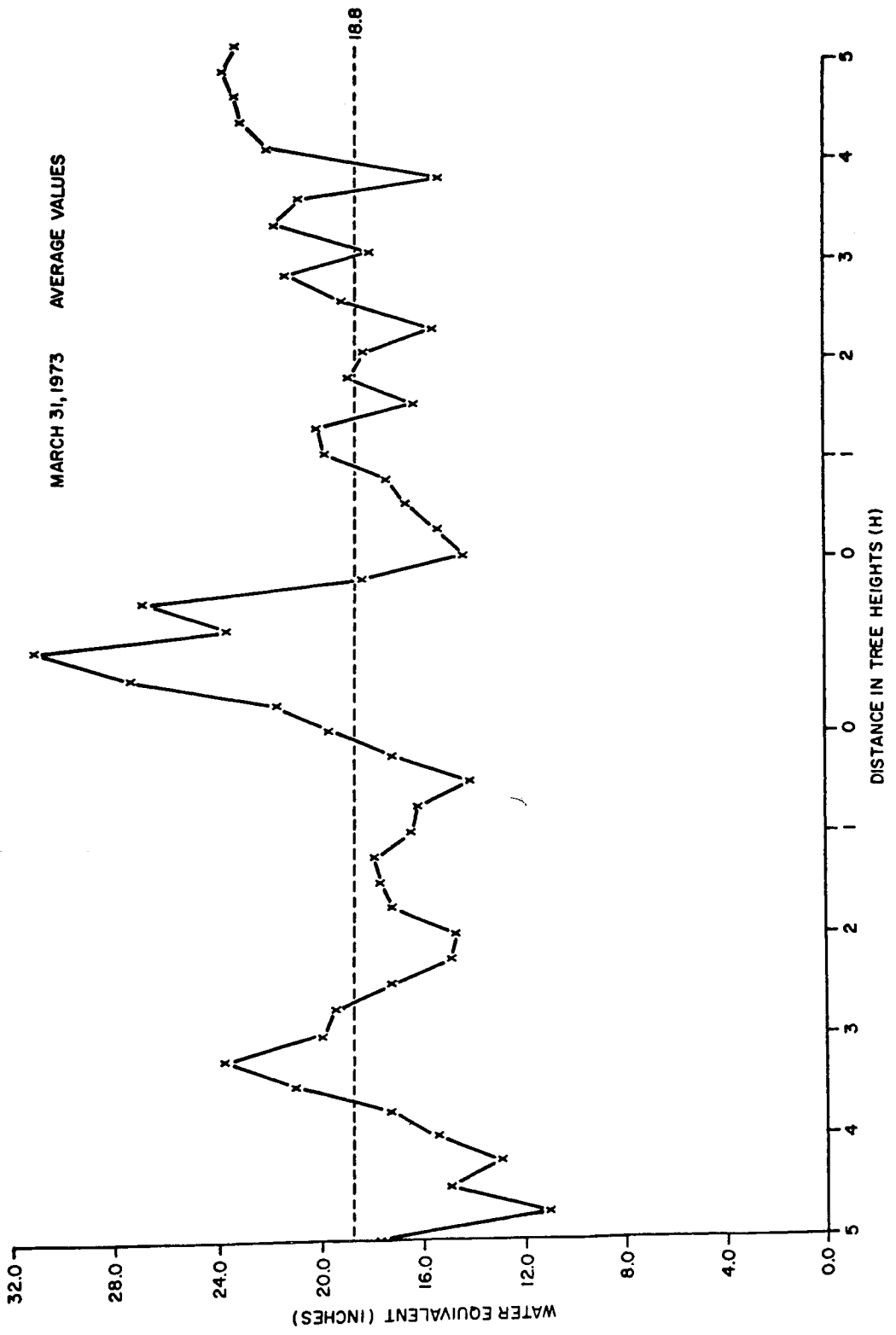
COMPUTED AVERAGE WATER EQUIVALENT FOR THE UNDISTURBED  
 FORESTED CONDITION FOR ALL STUDY SITES ON EACH  
 MEASUREMENT DATE

Site	Date	Average water equivalent of undisturbed forested condition (inches)
East	12/21/72	4.90
	1/12/73	6.49
	1/27/73	7.89
	2/10/73	6.35
	3/3/73	9.72
	3/17/73	15.37
	3/31/73	18.75
	4/17/73	14.01
	4/28/73	8.05
	5/12/73	1.05
Lower APS	12/22/72	4.37
	1/12/73	6.36
	1/27/73	7.05
	2/10/73	6.84
	3/3/73	9.37
	3/17/73	14.61
	3/31/73	17.87
	4/16/73	13.83
	4/28/73	8.75
	5/12/73	1.07
Upper APS	12/22/72	3.93
	1/12/73	6.04
	1/27/73	6.97
	2/10/73	6.86
	3/3/73	9.74
	3/17/73	14.36
	3/31/73	16.99
	4/17/73	13.68
	4/28/73	7.27
	5/12/73	0.05

Site	Date	Average water equivalent of undisturbed forested condition (inches)
Vespidae	12/23/72	0.32
	1/10/73	1.78
	1/27/73	1.83
	2/10/73	2.89
	3/3/73	4.56
	3/17/73	5.41
	3/31/73	5.48
	4/14/73	1.24
	4/28/73	0.00
	5/12/73	0.00
Annex	12/23/72	0.18
	1/10/73	1.74
	1/27/73	1.64
	2/10/73	2.53
	3/3/73	4.54
	3/17/73	6.02
	3/31/73	5.33
	4/14/73	1.58
	4/28/73	0.06
	5/12/73	0.00
Han-dah	12/23/72	1.32
	1/11/73	1.66
	1/27/73	1.94
	2/9/73	1.22
	3/3/73	1.76
	3/17/73	3.98
	3/31/73	5.90
	4/14/73	1.32
	4/28/73	0.00
	5/12/73	0.00
Navopache	12/23/72	0.52
	1/11/73	1.20
	1/27/73	1.16
	2/9/73	0.43
	3/4/73	0.40
	3/17/73	0.67
	3/31/73	1.01
	4/14/73	0.00
	4/28/73	0.00
	5/12/73	0.00

APPENDIX D

ILLUSTRATION OF THE AVERAGE WATER EQUIVALENT LINE  
REPRESENTING THE UNDISTURBED FORESTED CONDITION  
DRAWN THROUGH A SNOWPACK PROFILE



APPENDIX E

THE "NET" EFFECT OF THE OPENING AT EACH STUDY SITE  
ON EACH MEASUREMENT DATE

Site	Date	"Net" water equivalent due to opening's effect (inches)
East	12/21/72	5.05
	1/12/73	9.23
	1/27/73	14.28
	2/10/73	12.45
	3/3/73	22.19
	3/17/73	12.99
	3/31/73	15.75
	4/17/73	41.27
	4/28/73	27.85
5/12/73	14.35	
Lower APS	12/22/72	6.85
	1/12/73	10.55
	1/27/73	20.75
	2/10/73	9.45
	3/3/73	28.60
	3/17/73	15.30
	3/31/73	35.60
	4/16/73	1.90
	4/28/73	6.25
5/12/73	8.10	
Upper APS	12/22/72	-5.21
	1/12/73	-6.13
	1/27/73	-14.84
	2/10/73	-12.17
	3/3/73	-11.78
	3/17/73	-6.17
	3/31/73	19.97
	4/17/73	-34.71
	4/28/73	-36.94
5/12/73	-0.56	

Site	Date	"Net" water equivalent due to opening's effect (inches)
Vespidae	12/23/72	-2.86
	1/10/73	0.56
	1/27/73	-3.84
	2/10/73	-9.47
	3/3/73	-9.63
	3/17/73	-3.43
	3/31/73	-12.04
	4/14/73	-5.27
	4/28/73	0.00
	5/12/73	0.00
Annex	12/23/72	8.11
	1/10/73	4.23
	1/27/73	3.03
	2/10/73	5.31
	3/3/73	0.08
	3/17/73	8.79
	3/31/73	1.91
	4/14/73	4.16
	4/28/73	5.87
	5/12/73	0.00
Hon-dah	12/23/72	1.89
	1/11/73	4.07
	1/27/73	4.38
	2/9/73	3.44
	3/3/73	9.52
	3/17/73	6.71
	3/31/73	10.30
	4/14/73	3.89
	4/28/73	0.00
	5/12/73	0.00
Navopache	12/23/72	4.81
	1/11/73	2.10
	1/27/73	7.48
	2/9/73	6.29
	3/4/73	12.70
	3/17/73	12.51
	3/31/73	8.53
	4/14/73	0.00
	4/28/73	0.00
	5/12/73	0.00

APPENDIX F

METRIC CONVERSION TABLE

Unit used		Metric equivalent
1 inch	=	2.54 cm
1 foot	=	0.3048 m
1 sq ft	=	929.0 cm <sup>2</sup>
1 acre	=	0.4947 hectare
1 sq ft/acre	=	1877.9 cm <sup>2</sup> /hectare
1 acre-inch	=	102,801.6 liters

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