SNOW-AIR INTERACTIONS AND MANAGEMENT OF MOUNTAIN WATERSHED SNOWPACK

by

James R. Meiman and Lewis O. Grant

Colorado Water Resources Research Institute

Completion Report No. 57

Colorado State University

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OWRR Project No. B-073-COLO

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Department of Earth Resources
Department of Atmospheric Sciences

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submitted to

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U.S. Department of Interior
Washington, D.C. 20240

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ENVIRONMENTAL RESOURCES CENTER
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ABSTRACT

SNOW-AIR INTERACTIONS AND MANAGEMENT OF
MOUNTAIN WATERSHED SNOWPACK

Evaporation losses from mountain snowpacks amounted to approximately 60% of the snow season precipitation in an alpine setting and to approximately 45% in both a forest and a forest opening. Forest clearings similar to those studied should not result in greater snow evaporation losses if they are kept small enough to prevent wind transport of snow. Periodic removal of ridgeline snow deposits into the cirque below resulted in an increase of water yield equivalent to 240 acre-feet of water per mile of ridgeline treated. The estimated cost of the increased runoff was approximately $50 per acre-foot discharged from the cirques. A water-budget analysis of the alpine feeder area indicated that nearly 80 percent of the seasonal precipitation was transported out of the region by the end of the winter study period, 30 April. Only 23 percent of this total transport (18% of seasonal precipitation) was caught in the natural cornice deposits along the ridgeline. It was shown that the cornice location is an inefficient place to store the windblown snow. Less than one-third of the winter storage in these ridgeline deposits was available for runoff. The remaining two-thirds was lost to either evapo-sublimation or late melt occurring after the runoff from the cirques had ceased. In the study area there is no carry-over of the ridgeline deposits into the next season. The water-budget analyses for the cirques indicated that nearly 75 percent of the water stored in the cirques during the winter period was realized as runoff during the melt period.

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I. INTRODUCTION

The basic objectives of this study were:

1) Evaluate the interface transport of water vapor between snow surface and atmosphere in alpine, forest, and forest clearing exposures.
2) Test effectiveness of management techniques to reduce vapor losses from alpine zones thereby increasing water supplies.

The experimental work was conducted at two different locations with the alpine vapor transport and management study centered near Climax, Colorado at an elevation of 12,000 feet and the forest and forest clearing studies conducted at Pingree Park, Colorado at an elevation of 9,000 feet. The results from the Pingree Park studies on snowpack evaporation from forested regions are presented in Chapter II and the results from the alpine studies are presented in Chapter III.

The importance of snow evaporation in the overall water balance of mountain lands is poorly defined. This study is aimed at a better understanding of the amount, timing, spatial distribution, causative factors, and possible reduction of these losses. It is anticipated that a better understanding of these processes will lead to better definition of practical management measures to increase usuable water supplies from the snowpack zone of the Rocky Mountains and similar areas.

Recent state-of-the-art papers on snow evaporation and related management practices include those by Slaughter (1970), Martinelli (1960, 1965), Schmidt (1972), Tabler (1971), and Meiman (1969). Further analysis of current literature along with detailed presentation of procedures and discussion of results may be found in the two theses that resulted from this project by Harlan (1974) and Santeford (1973).

II. FOREST SNOWPACK EVAPORATION

A. Methods and Procedures

The study was conducted in the Colorado Rockies at Colorado State University's Pingree Park Forestry Summer Camp. The elevation is 2740 meters (8990 ft.) and the site is located in a glaciated valley bottom which is flanked on both sides by lateral moraines.

The measurements were taken in the center of a clear-cut, 140 feet (43 m) in diameter, which is two to three times the surrounding tree height, and in the forest site composed entirely of Lodgepole pine (*Pinus contorta*) with 50-70% canopy density. The test periods were 4 1/2 to 5 1/2 hours in the morning and afternoon, and 14 to 16 hours at night, which gives a representative measurement for a 24-hour period.

There were a total of 83 test periods for 1972 through 1974. During February of 1973, 13 tests were conducted but no meteorological data was recorded at that time. The remaining 70 test periods were during December of 1973 through April of 1974.

A summary of the evaporation measurements are as follows:

	Morning	Afternoon	Night
February 1973	5	3	5
December 1973	4	4	3
January 1974	7	8	6
February 1974	3	4	2
March 1974	4	5	2
April 1974	7	9	2

Total = 83 periods.

Three evaporation pans were installed at each study site. The evaporation pan used in this study was 14.48 cm inside diameter with a plexiglass wall thickness of 3.0 mm. The total height of the pan was 23.0 cm. and the depth to the false inner bottom was 15.3 cm. This false inner bottom is designed to simulate natural snowpack conditions. It provides a repository for storing snowmelt in the lower third of the pan. Three tension tubes are afixed to the bottom side of the tension table to avoid an abnormal amount of melt-water present in a snow core sample. The tension tubes are 7 1/2 cm. long, which provide adequate water tension to drain melt-water from a snow core, ensuring a more natural approximation of a snowpack. At the end of a test period, both the remainder of snow and melt-water are measurable to obtain the evaporation rate.

If the snow was a coarse or powderey consistency, the pans were prepared by shoveling snow into the top repository and smoothing the top surface with a hand level. When snow conditions such as wind or melt slabbing occurred on the snow surface, additional care was taken in the snow pan preparation. Here, a cutter was made from a piece of stove pipe having the same inside diameter as the snow pan. This was used to obtain a surface core for the snow pans. Needless to say, patience is needed in such a process to prepare six pans for every test period. The gross weight of six sample pans were determined on an O'Haus triple beam balance to the nearest gram, which gives a measurement error of better than $\pm$0.06 mm. of water per unit area.

The evaporation site was left undisturbed with the exception of the test holes. The cutter was used again to excavate the test holes where the snow pans were placed after the initial weight was recorded. The same snowpack test spots were used the entire winter for each pan. After placing the snow pans in their respective evaporation locations, additional work must be done around the rim of each pan to insure continuous snow contact with the container. Pressing additional snow against the sides and up to the top of the snow pan's rim insures proper snow pan placement.

Temperature, relative humidity and wind velocity were continuously recorded at the open, forest and the local weather station. This enabled a correlation to be made of these meteorological factors at the weather station to those at the opening and the forest. Air temperature and air vapor pressure were recorded by hygrothermographs which were located inside instrument shelters. The average wind velocity was measured with a totalizing anemometer. All three hygrothermographs and anemometers were calibrated in one location before evaporation tests were initiated. The temperature traces of the hygrothermographs were compared to a standard thermometer a number of times and gave exceedingly good readings; no calibration curves were needed.

The average monthly height for the instruments above the snowpack surface is shown in Table 1.

Table 1

AVERAGE MONTHLY HEIGHT OF INSTRUMENTS ABOVE THE SNOWPACK SURFACE

Month	Instrument Height* inches (cm)
December	44.8 (126.5)
January	34.0 (86.4)
February	33.0 (83.8)
March	31.3 (79.5)
April	25.0 (63.5)

*Instrument height from soil surface is 1 1/2 meters.

The snowpack depth was secured from snow stake data located in a forested site near the Pingree Meadow. This data gave a representative approximation of the snow depths for both the forest and the opening on a monthly basis.

Additonal on-site measurements of the snow surface temperature, air temperature, and air vapor pressure were recorded in the opening and in the forest. For each test period there are three specific times for taking such measurements. The times were 0700, 0930, 1130 M.S.T. for morning tests, 1230, 1430, 1630 M.S.T. for afternoon tests and 1900, 2300, and 0700 M.S.T. for the night tests.

A wet-dry bulb fan psychrometer was placed inside the instrument shelters to obtain the air vapor pressure at both sites. A standard Weather Bureau mercury thermometer graduated in degrees Fahrenheit was placed in the shade on the snow surface to determine the snow surface temperature. Air temperature was also recorded by using the dry bulb thermometer reading of the psychrometer. An aneroid barometer at the weather station was read four times daily and used with all of the wet-dry bulb records to obtain the air vapor pressures.

Three evaporation pans were used in both the opening and the forest. From the resultant weight loss or gain, an average weight change was determined for each site during each test period (morning, afternoon, or night).

Measuring accurate air vapor pressures at low temperatures with the use of psychrometers leaves much to be desired. The wet and dry bulb readings were used not only for the vapor pressure of the air, but also for the vapor pressure gradient at both sites. With the use of the barometric pressure, the calculation of the air vapor pressure was obtained by using the Smithsonian Meteorological Tables #95 (saturation vapor pressure over water), #97 (saturation vapor pressure over ice), and table #99 (reduction of psychrometric observations) to secure the most accurate readings during the constant periods of low air temperatures.

The snow surface temperature values were used to determine the snow surface vapor pressure. Table #97 (saturation vapor pressure over ice) was used to determine the snow surface vapor pressure (Smithsonian Meteorological Tables, 1966). The vapor pressure gradient was then computed as the difference between the average air vapor pressure and the average snow surface vapor pressure for each test period.

Wind miles were read directly from the three totalizing anemometers. The resulting miles of wind for each anemometer were then divided by the total hours of time between the beginning and the conclusion of a test period, giving an average wind speed in M.P.H. which were then converted to meters per second.

B. Results and Analysis

During 1972-74, there were a total of 83 test periods of which thirty were morning tests, thirty-three were afternoon tests, and the remaining twenty were night tests. The basic data is presented in Appendix I.

Condensation gain for an entire test period occurred only twice in a total of 83 tests, but signs of condensation were evident on a few other night tests. During such tests, the evaporative loss out-weighed the small, early morning condensation gain.

An unpaired t-test was used on the three evaporation pan values in both sites for every test period to determine which evaporation tests had evaporation rates that were significantly different ($\alpha = 0.05$). Out of the 83 tests, 42 were significantly different. the majority of such significantly different data occurred almost entirely during the afternoon and night tests with the evaporation rates being greater in the open than in the forest during the afternoon and just the opposite during the night tests.

The average evaporation for the second season (1973-74) had 37 significantly different test periods and is shown in Table 2.

Table 2

SUMMARY OF SIGNIFICANTLY DIFFERENT EVAPORATION RATES FROM THE TWO SITES (mm. OF WATER PER HOUR)

	Morning	Afternoon	Night
Open	0.063	0.077	0.021
Forest	0.042	0.044	0.024

The average evaporation (mm. of water per hour) for the remaining 33 tests of 1973-74 was 0.037 for the morning periods, 0.057 for the afternoon periods, and 0.029 for the overnight periods.

There was evidence of a diurnal cycle of evaporation losses during the day and night periods. The afternoon tests had consistently higher evaporation rates in both the opening and the forest than did the morning and night test periods.

By weight-averaging significantly and nonsignificantly different data segregated into their appropriate test periods and test sites, an evaporative loss from both sites for 1973-74 was estimated for December through April. The opening had an estimated loss of 134.8 mm. and the forest 122.4 mm for this five month period (Table 3).

Table 4 displays the maximum, minimum and average evaporation rates measured at both sites for each test period for all data collected during the period from December 1972 through April 1974.

Table 3

TOTAL ESTIMATED EVAPORATION FOR DECEMBER-APRIL (mm)

	Morning	Afternoon	Night	Total
Open	32.09	46.80	55.95	134.84
Forest	26.45	33.08	62.91	122.44

The product of the wind velocity and the vapor pressure gradient was correlated against the observed evaporation rates. The results are shown in Table 5. Figure 1 graphically displays the two sites comparing the observed and calculated evaporation rates from the prediction equations given in Table 5.

All of the meteorological variables at each evaporation site were correlated with simultaneously recorded meterorological variables at the local weather station. The r-squared value, standard error, and the beta coefficient are presented in Table 6.

Table 4

AVERAGE, MAXIMUM AND MINIMUM EVAPORATION LOSSES FOR BOTH SITES (mm. OF WATER/HOUR AND DAY OF OCCURRENCE)

Opening

	Morning	Afternoon	Night
Average Loss	.048	.070	.024
Maximum Loss	.114 (4/6)	.185 (2/4)	.096 (1/9)
Minimum Loss	.004 (4/19)	.004 (4/18)	.0004 (1/26)

Forest

	Morning	Afternoon	Night
Average Loss	.039	.048	.029
Maximum Loss	.118 (2/4)	.188 (1/13)	.079 (3/1)
Minimum Loss	.003 (4/19)	.006 (4/17)	.0008 (4/18)

Table 5

EVAPORATION RATE PREDICTION EQUATION BY USING ON-SITE METEOROLOGICAL VARIABLES

OPENING

$$E = k \cdot (u) \cdot (e_a - e_s)$$

where k = coefficient for the opening
= (0.249)
E = evaporation rate in the opening (mm. water per hour)[1]
u = average wind velocity (m.p.h.)
$e_a - e_s$ = average vapor pressure gradient (in. of Hg)

$r^2 = 0.83$
s.e.= 0.0293
$\bar{E} = -0.05314$

FOREST

$$E = k \cdot (u) \cdot (e_a - e_s)$$

where k = coefficient for the forest
= (0.285)
E = evaporation rate in the forest (mm. water per hour)
u = average wind velocity (m.p.h.)
$(e_a - e_s)$ = average vapor pressure gradient (in. of Hg)

$r^2 = 0.76$
s.e.=0.0259
$\bar{E} = -0.0408$

[1]Wind velocity and vapor pressure gradient averaged over morning, afternoon or night time periods.

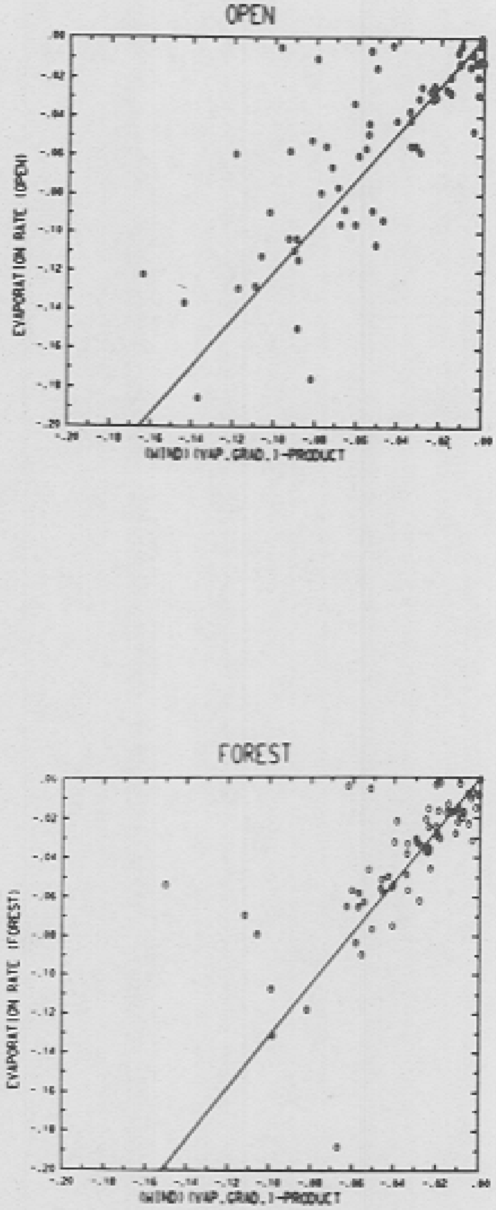

Figure 1. Graphical presentation of the observed and calculated evaporation rates for the opening and the forest (mm. of water loss per hour).

Table 6

RELATIONSHIP OF METEOROLOGICAL DATA OF THE WEATHER STATION TO THAT OF THE EVAPORATION SITES

Variable	r-squared	Number of Observations	Stand. Error	Average Variable Value[1]	Beta Coefficients
OPEN EVAPORATION SITE					
Air Temperature Deg. F. (deg. C.)	0.95*	70	2.68 (1.49)	+32.54 (+0.30)	+0.992
Air Vapor Pressure In. of Hg (mb.)	0.52*	70	.0198 (.653)	.07159 (2.424)	+0.508
Wind Velocity m.p.h. (m./sec.)	0.74*	70	1.12 (0.50)	4.41 (1.97)	+0.450
FOREST EVAPORATION SITE					
Air Temperature Deg. F. (deg. C.)	0.97*	70	1.72 (0.96)	+31.05 (-0.53)	+0.928
Air Vapor Pressure In. of Hg (mb.)	0.51*	70	.0250 (.847)	.0806 (2.73)	+0.629
Wind Velocity m.p.h. (m./sec.)	0.63*	70	0.75 (0.34)	2.26 (1.01)	+0.236

* Relationship Exists ($\alpha = 0.05$)
1 Average Meteorological Factor at the Evaporation Site.

For the open site, the average air temperature was highly correlated with the average weather station temperature, followed by a moderate correlation with the average air vapor pressure and the average wind velocity. In the forest, the air temperature was again highly correlated with the weather station, followed by a moderate correlation found with the average wind velocity and the average air vapor pressure.

III. MANAGEMENT OF WINDBLOWN ALPINE SNOWS FOR MAXIMIZING STREAMFLOW

A. Procedure

A water budget procedure for two (paired) cirques in the Chicago Ridge area of central Colorado has been used. The water budget has specifically included considerations of: (1) the precipitation in the area, (2) the transport of snow from the "feeder" area on the windward slope of the alpine area, (3) the collection of snow in the lee side cirque cornice, (4) the transport of snow into the lower portions of the cirque, and (5) the streamflow which occurred. Each of these terms has been evaluated. Management techniques have then been evaluated by comparing the streamflow yield between the paired cirque for separate years when management was and was not applied to one of the cirques.

Water budget in the feeder area

The water-budget in its simplest form, i.e.,

inflow = outflow + change in storage,

was utilized in the feeder area. By defining the boundary of the area in such a way that negligible transport of blowing snow into the area was anticipated, the only inflow to be considered is that of direct precipitation. The time period for which the budget was considered extended from November through April. During this entire period, the ground was frozen and snowcovered and thus outflow from melt runoff was not a factor to be considered. The only outflow during this winter period was that which resulted from the direct transport by the wind and included both the solid and vapor states. By measuring the direct precipitation and the change in storage of the water equivalent of the snow pack for any given period, the outflow could be calculated as the residual.

The primary system for measuring the precipitation and change in storage consisted of eight precipitation gauges equipped with unbridled Alter shields placed at selected locations within a network of 39 snow sampling stations. At each precipitation gauge snow survey data were also obtained. The location of each of these stations can be seen in Figure 2. Once the data collection began, it was apparent that although the snow survey stations were arranged in a 600-foot square grid the mean of the data was not representative of the actual conditions. Therefore, isohyetal maps of the snowpack water equivalent were constructed encompassing all available data ranging from topographic features to field observations of drift patterns.

The catch efficiency of the precipitation gauges was also questioned and thus additional snow survey measurements were taken in the area near timberline to serve as an auxiliary measurement. It had been anticipated that a two week time period between successive snow surveys would be used. This, however, was not always met due to severe weather conditions.

Water Budget in the Cirques

The water-budget for the cirques is similar to that for the feeder area except that the equation contains additional terms. The inflow contains all moisture entering the cirque from the beginning of the winter period through the end of the melt season and includes the direct precipitation from both winter snows and summer rains, the snow stored in the cornice-winds lab deposit, and the direct transport of blown snow from the feeder area into the cirque. The last two terms, i.e., the cornice-winds lab deposit and the direct transport, both originate as snow blown out of the feeder area and will be discussed in detail in the following sections. The outflow from the cirques contains both the evapo-sublimation losses and the surface runoff. In the seasonal budget, the change in storage was assumed to be zero. This assumption was based on the intermittent nature of the surface runoff and the geological formations as previously described. For the various sub-periods throughout the entire study period, the change in storage at times included the change in water equivalent of the various snow deposits.

The direct precipitation onto the cirques was determined by the average of three precipitation gauges located at the points indicated on the map of Figure 2. As a check on the efficiency of these gauges, periodic snow surveys, consisting of from 10 to 18 sampling stations, were performed in each of the cirques throughout the winter period. Near the end of the winter period when the maximum water content of the snowpack was anticipated, as well as shortly after the melt had begun, extensive snow surveys consisting of 12 transects across the two cirques and containing more than 250 sampling stations, were performed. Due to avalanche danger, approximately 20 percent of the cirque area was not surveyed. However, nearly 70 percent of this area which was not surveyed was analyzed through the use of stereo photographs and snow depth markers placed in the area during the previous summer period.

The surface outflow from each of the cirques was determined from flow measurements obtained from a continuous record of the stage upstream of a dam in which a 90° "V" - notch weir was placed. In view of the geologic structure, it was assumed that the sub-surface flow was negligible, and thus any seepage which did occur would be included with the evapo-sublimation losses in a combined term simple referred to as losses.

Proportioning of the Total Transport

The total transport of moisture from the entire potential feeder area was subdivided into that quantity which passed over the crest of each of the cirques using the procedure outlined below.

The analysis is based on the average hourly wind speed and direction for each of the hourly periods between successive snow surveys. Knowing the size of the effective feeder area for each of the cirques under various wind directions, as well as the transport from the total area for the entire time interval, and the minimum velocity at which noticeable transport would occur, the transport over each of the cirques can be estimated from a simple ratio of the summation of effective feeder areas to the summation of the total potential feeder areas. Although this analysis is based on numerous assumptions, it is believed to give a reasonable estimate of the actual quantities involved and is more reliable than any of the other methods considered.

Main Components of the Transport

The total transport from the feeder area as defined above contains all water leaving the area through both direct transport of snow and evapo-sublimation losses from the main snowpack. The direct transport term can be divided further into the portion caught in the cornice-windslab deposit, the portion carried by the wind into the lower valley, the portion which precipitates directly into the cirques referred to as fallout, and the losses resulting from both evapo-sublimation losses during the transport process and extensive transport beyond the limit of the study area. By combining the evapo-sublimation losses from the main snowpack with the losses occurring during transport, the following mass relationship is obtained:

$$L = T - F - C - V$$

in which

L is the total losses,

T is the total transport from the feeder area,

F is the fallout,
C is the cornice catch, and
V is the transport in to the lower valley.

When the total transport from the potential feeder area is used for "T" in the previous relationship, all other terms refer to the entire area. If however, the transport over each of the cirques as obtained from the previous analysis is used for the value of "T", then all other terms are for the particular cirque under investigation.

Examination of the above relationship reveals that all terms on the right can be evaluated from direct measurment. The appropriate value for the transport can be obtained from the previous considerations. The fall-out was determined by performing replicator profiles in the cirques on selected days when no precipitation was occurring yet visible transport of blowing snow was noted at the ridgeline. These replicator profiles consist of a series of measurements of the precipitating snow crystals at increasing distances from the ridgeline. The snow crystal replicator used was one developed at C.S.U. and consists of a closed box into which a small opening is cut in the upper surface. Within the box, a continuous strip of 35 mm film base coated with a thin layer of liquid plastic passes under the window. Any snow particle which passes through the opening in the box strikes the moving film strip. As the liquid plastic dries the impression of the particle remains in the plastic layer and serves as a permanent record or replication of the particle. Through statistical methods, these data are then reduced to a measure of the actual precipitation rate and thus the mass of snow which was falling on a given area over the given time period. In addition to the replicator profiles, numerous visual observations were made under similar weather conditions to further substantiate the results of the replicator data.

When the anticipated circulation pattern of the air flow over the ridge is considered, an area of general downward motion is expected on the leeward side of the ridge. The snowpack in this region should be somewhat larger than that of the surrounding areas as a result of the transported snow carried by this circulation. In hopes of determining the magnitude of such increased accumulations, snow surveys were performed in the region extending from the cirques to east (downwind for several miles).

The volume of snow caught in each of the cornice-windslab deposits was determined by utilizing conventional survey techniques and stereo paired terrestrial photographs obtained with the use of a K-24 camera located in the cirques. From the field measurement and the photograph measurements, the cross-sectional area at various locations along the formation, and thus the volume of the deposit, was determined. By combining these volume measurements with density measurements obtained from core samples of the cornice deposit, the actual water content of the deposit was determined. By performing these measurements at the time of each snow survey in the feeder area, the water-budget analysis could be performed on each of the sub-periods as well as the entire season.

Management Technique

Several management techniques have been considered and tried. They include guiding the snow along the feeder area into the cirque, avalanching the cirque cornice to concentrate the snow and to make a fresh storage area for new drifting snow, and treatment of the snow cover to reduce evaporative losses. The main technique tested was the avalanching of the cirque cornice.

Avalanche Procedure and Evaluation Technique

Two different procedures were used to induce the artificial avalanches.

One consisted of placing surface directed explosives at various spacing along the cornice with several charges detonated at one time. The other method relied on the conventional technique of boring a hole into the formation, loading it with dynamite, back-filling, and then when a series of several such charges had been prepared, detonating the entire series at once. The actual size of the various charges, as well as the spacing, varied considerably between the different avalanche events.

The effect of the avalanching as a mangement technique was determined utilizing much of the data previously discussed. The overall effect of the avalanching was determined from the difference in unit runoff from the two cirques as determined from the water-budget analyses.

By defining the catch efficiency of the cornice as the ratio between the water caught in the deposit and the total transport over the cirque, any change in this ratio represents, in part, the effect of the cornice deposit on the rate of further deposition. If the removal of the deposit does have a significant effect on the rate of deposition, then there should be a significant difference between the catch efficiencies for the treated and untreated deposits. This difference should be evident for the various time periods following each of the avalanche events as well as for the entire season.

In the previous discussion it was stated that an increase in runoff was anticipated from two different sources, namely an increase in the cornice storage and a reduction in the evapo-sublimation losses from the ridgeline deposit. Although these two factors are distinctly different, the effect of each is not directly determinable from the data. With the periodic avalanching, there is no additional accumulation of material in the cornice formation, but rather a replacement process where new snow is being substituted in the cornice formation for that which was relocated by the avalanching. Since the indicated increase in water resulting from an increase in the catch efficiency of the cornice is also relocated in the cirques, the effect of the two processes are not directly separable. However, an estimate of the relative size of the two factors can be obtained from the data analysis on the control system. If it is assumed that the unit losses from the ridgeline deposits on the two cirques are the same, and that the losses from the main snowpack in the cirques and the losses from the ridgeline deposits are in proporation to the evapo-sublimation potential in each region, then an estimate of the losses which occurred from the ridgeline deposit can be obtained. The details of this procedure are best illustrated through the use of the actual computations as presented in the chapter on the analysis of the data.

B. The Study Area

The study area involves not only the alpine region but also the cirque region in which the avalanched material was to be deposited. Thus, the cirques were as important as the ridgeline area in the selection of the study site. With the aid of field personnel well acquainted with the general region, the study area shown in Figure 2 was selected. This area was further subdivided into three sub-areas for individual study. These include the two cirques on the leeward side of the ridge and the entire alpine area located in a westerly direction from the ridge to timberline. This latter area, which will be referred to as the feeder area, presumably serves as the main supply area for the transported snow which is deposited in the cornice formation.

The feeder area shown in Figure 3 measures approximately 6,000 feet in a north-south direction and 4,000 feet in an east-west direction and

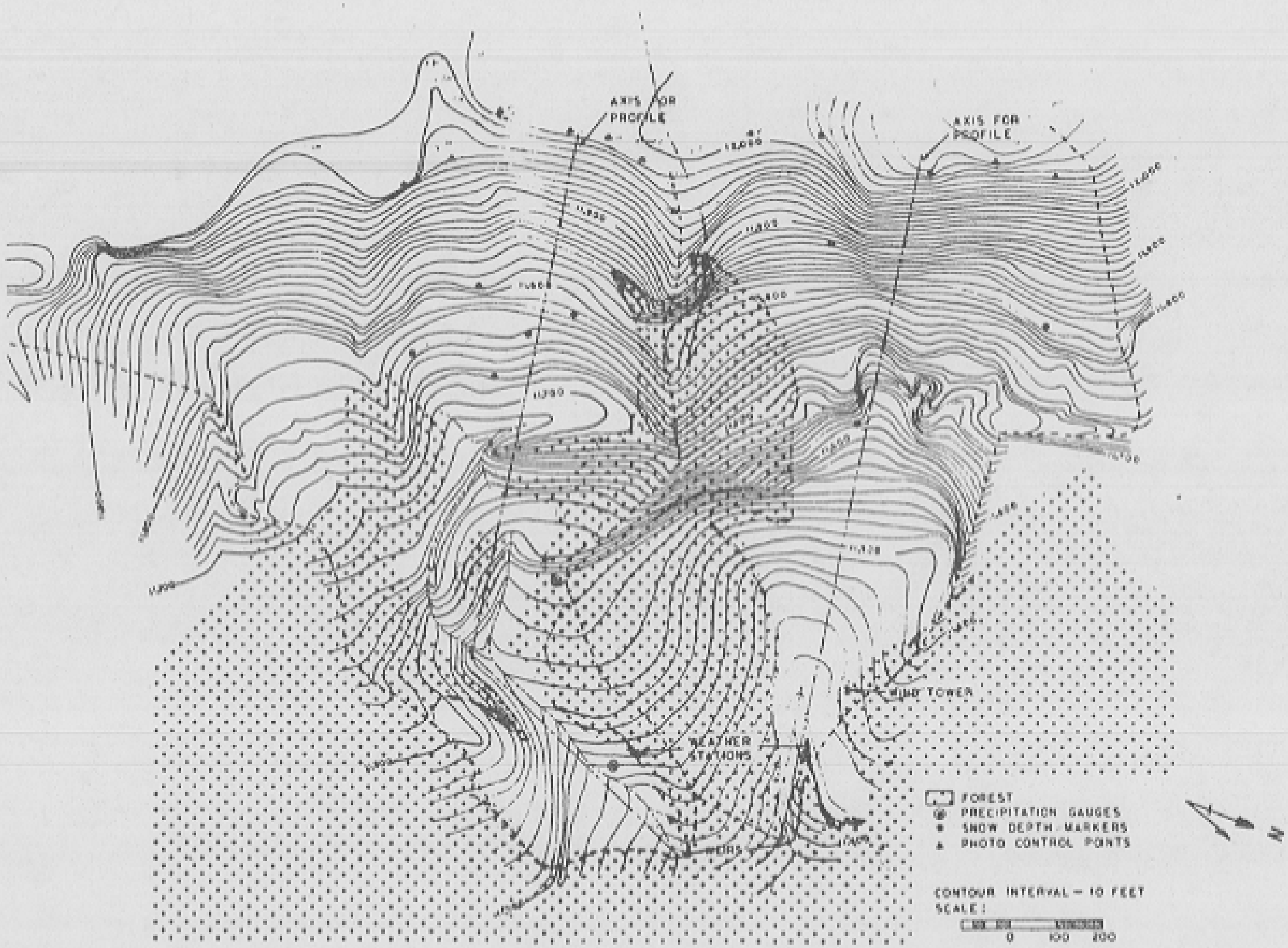

Fig. 2. Topographic map of the cirques.

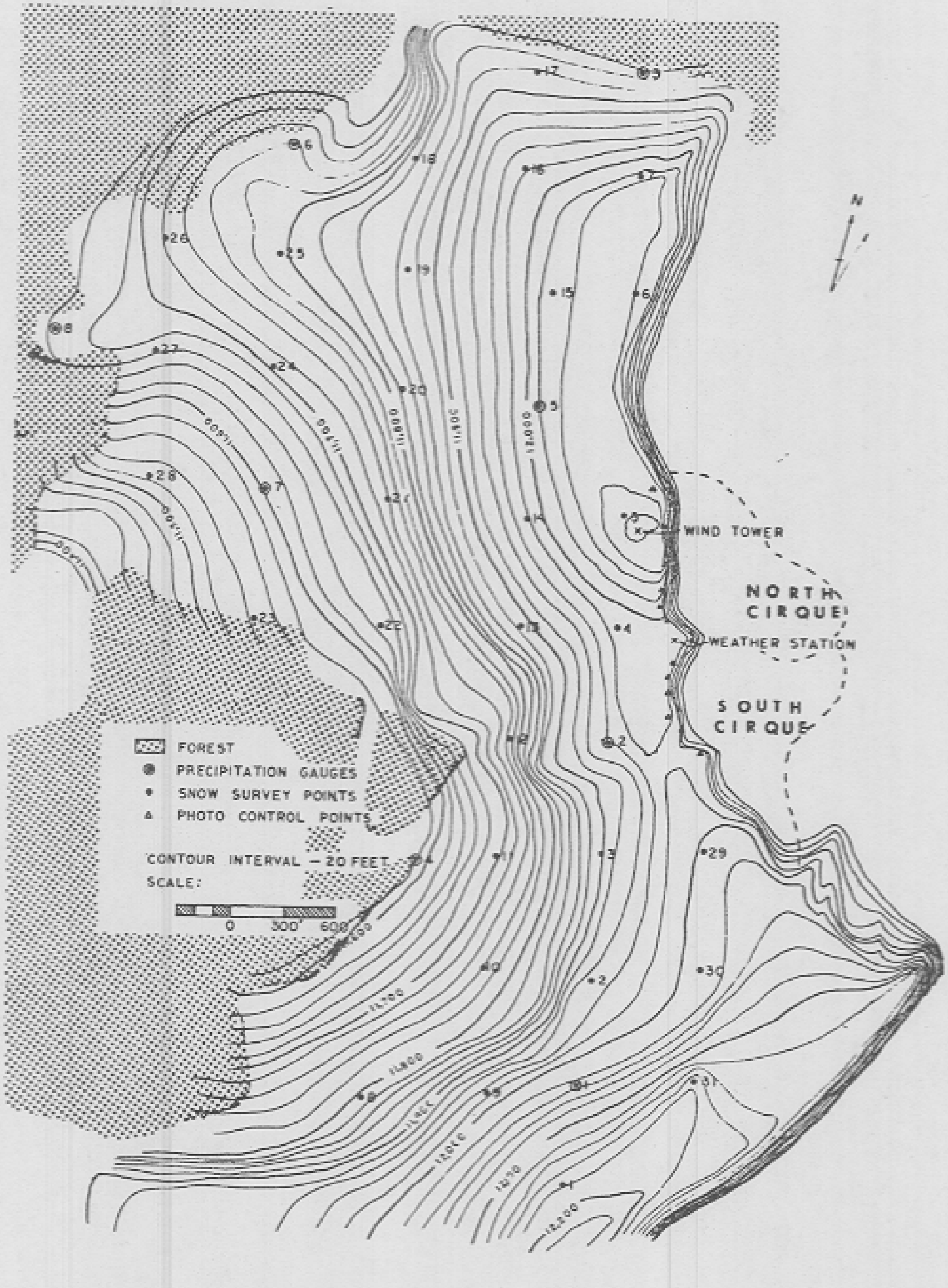

Fig. 3 Topographic map of the alpine feeder area.

contains 402 acres. This area, bound on the north and west by timberline, the south by a steep rise of over 800 feet, and the east by the ridgeline, is covered by a thin soil mantel which supports only tundra type vegetation. The area within several hundred feet of the ridgeline consists primarily of small pieces of broken rock which support only sparce vegetation. During the winter this ridgeline area is generally blown free of any appreciable snowcover.

The entire area is underlined by sedimentary formations which dip at approximately 15 degrees to the west. Near the lower boundary of the area on the west, at an elevation of approximately 11,600 feet, are located several springs which ultimately form the headwaters of Jones Gulch. These springs are in the general location of precipitation gauges number 4 and 7 as shown in Figure 3. These springs, as well as a lower set at an elevation of approximately 11,300 feet, are intermittent and cease to flow in late summer and early fall, respectively.

The two cirques are typical of alpine cirques. They each have the characteristic "U" shaped valley covered with tundra type vegetation and flanked on each side with forested areas of Engelman Spruce and Sub-alpine Fir. The encroachment of the valley floor by the forest is limited by regular natural avalanches.

The topographic map of Figure 2 shows that the two cirques are approximately the same size; the south cirque containing 28.9 acres while the north contains 24.8 acres. The south cirque, however, has a much longer ridgeline, approximately 1800 feet, as compared to the nearly 1000 feet on the north cirque.

C. Research Results

The data presented are for two years of a continuing study being conducted along the continental Divide in central Colorado near Climax. The study area consists of three main parts: the alpine region located to the west of the ridgeline and extending to timberline, and two cirques located on the east or leeward side of the ridge. The analysis of the hydrometeorologic data for the two cirques indicated that the two appear to be similar with regards to their hydrologic response. Based on this apparent similarity, one of the cirques was chosen as a control while the other was subjected to a management effort consisting of four artificially induced avalanches of the cornice deposit. Water-budget analyses were performed on the data from various sub-periods as well as for the entire season. From these analyses, the total transport of moisture from the alpine area was computed. Utilizing a precedure based on the effective transport area associated with each of the cirques, the transport over each of the two study cirques was estimated. The total moisture crossing the crest of each cirque was divided into that which was caught in the cornice deposit, that which simply settled into the lower reaches of the cirque and was referred to as "fallout," that which was carried by the general circulation into the lower valley beyond the outflow point of the cirques, and that which was considered as losses. In this analysis the losses were calculated as the residual of the other measured terms of the water-budget.

The effect of the management effort on the amount of blowing snow that was caught in the cornice deposits was determined by comparing the catch efficiency of the manage deposit, to that for the unmanaged deposit. Knowing the amount of water stored in each of the cirques at the beginning of the melt period, a water-budget analysis was used to determine the over-all effect of the management effort.

A more detailed description of this research is available in the report by Santeford, Henry S., Jr. (1972), Management of Windblown Alpine Snows. Documentation of the comparison between the cirques under untreated conditions was continued during 72-73, and 73-74 winter seasons. These, in general, confirm the relationship between the two cirques and help establish baseline conditions for further tests of management practices.

IV. CONCLUSIONS

A. General

The results from both study locations indicate the importance of vapor losses from snow in the Rocky Mountain Region. In the alpine situation approximately 60% of the snow season precipitation was lost either directly from the snowpack or during subsequent wind transport. The losses from the forest and forest clearing were similar and represented approximately 45 % of the December through April precipitation. These results appear reasonable when considering the strong wind effects at the alpine site as contrasted with the forest and forest clearing sites where wind transport of snow was minimized.

The major management implications of the findings of this study are the necessity to minimize the opportunity for snow transport to occur in forested regions and the potential for trapping and concentrating blowing snow in the alpine to reduce sublimation losses during transport. An additional implication of the findings is that for both the alpine and forest situation any practical technique that could be developed to reduce direct vapor losses from the snowpack during winter would be of value in conserving significant amounts of water.

B. Forest and Forest Clearing

The following conclusions are specific to the forest and forest clearing studies:

1. Depending on the time of day, significantly different evaporation rates were found in the forest and the adjacent opening. The

opening had higher amounts of evaporation loss during the afternoon than did the forest site, whereas at night the forest had a significantly greater losss.

2. Even though wind velocities were higher in the open regardless of the test period, greater evaporation rates in the forest at night appeared to result from the higher snow surface temperatures in the forest.
3. Prediciton of evaporation rates by the use of on-site meteorological factors (i.e., vapor pressure gradient and wind velocity) gave an r^2 and standard error of 0.83 and 0.029 mm $hr.^{-1}$ respectively for the opening and in the forest, 0.76 and 0.0259 respectively.
4. Air temperatures at the Pingree Weather Station correlated well (r^2 range of 0.95 to 0.97) with the air temperatures of the evaporation sites. The air vapor pressure and the wind velocity showed a poorer correlation, (r^2 range of 0.51 to 0.52) and (r^2 range of 0.63 to 0.74) respectively.
5. A prediction of the evaporation loss from the snowpack in both the open and the forest is difficult to determine with confidence by using the meteorological factors at the standard weather station located in the nearby Pingree Meadow.
6. Based on the data from the test periods, loss from the open and forest snowpack was 134.8 mm and 122.4 mm, respectively, for the five months during December through April of 1973-74.
7. The opening had a morning, afternoon and night evaporation loss of 32.1, 46.8, and 56.0 mm, respectively, whereas in the forest, the morning, afternoon and night losses were 26.4, 33.1, and 62.9 mm, respectively, for 1973-74.

8. These results suggest that creation of small openings in the forest, of one to several tree heights in diameter would not greatly increase snowpack evaporation under conditions similar to those studied (i.e., with a maximum wind velocity near the surface of seven m.p.h.).
9. When considering the shallow nature of snowpack depths at this elevation, an evaporative loss of one inch per month during low snowpack years may determine the ability of sites such as these to produce off-site water yields during snowmelt.

C. Alpine

1. Approximately 20 percent (21.7 ± 3.9%) of the seasonal precipitation in the feeder area remained in the snowpack at the end of the winter period (24 April 1972). Considering the large evapo-sublimation potential which occurred following the time of this last snow survey, it is questionable whether even this small percentage of the precipitation was available by the time the melt began.
2. Nearly 80 percent (78.3 ± 4.0%) of the seasonal precipitation which fell in the alpine was transported out of the area by the wind. This transport included both the atmospheric water-vapor from the evapo-sublimation of the snowcover and the solid state snow physically carried by the wind. In absolute measures, this transport represents approximately 750 acre feet (744 ± 37) of water from the 402 acre study area.

3. Assuming the cornice deposit on the unmanaged south cirque was representative of the formations along the entire ridgeline of the study area, only 23.1 ± 0.9 percent of the transported snow was caught in the ridgeline deposits. This value represents a cornice storage of approximately 140 acre feet of water per mile of ridgeline.
4. No evidence of any measurable fallout of the transport material into the cirques or transport of snow into the lower valley could be found. In the analysis, these two terms were, therefore, assumed as zero. These findings are supported by the theoretical model for predicting sublimation from transported snow developed by Schmidt (1972).
5. The portion of the transport that was not caught in the ridgeline deposits, approximately 77 percent, is believed to have sublimated from both the inplace snowcover in the alpine as well as during the transport process. During the early and mid-winter periods, it is believed that the major portion of the sublimation is occurring during the transport process, and particularly after the blowing snow leaves the ridge and enters the expanding airflow on the leeward side. During late winter and early spring, the inplace evapo-sublimation loss is believed to be more significant than that for the earlier portions of the season.
6. When the water stored in the ridgeline deposits is combined with the storage in the alpine snowcover, a total of only 39.9 ± 4.4 percent of the seasonal precipitation in the feeder area was

still in the immediate area by the end of the winter study period. The remaining portion of the seasonal precipitation, nearly 60 percent, is the quantity previously discussed in conclusion number 5.

7. A sizeable portion of the water stored in the ridgeline cornice deposits at the end of the winter period remains at the ridgeline location after the runoff from the cirques has ceased. For both the managed and unmanaged cirques, this quantity represented approximately 30 percent of the maximum winter storage.
8. During the summer and early fall, the ridgeline deposits in the study area completely melt with no carry-over into the next season. The water which had been stored in these deposits when the runoff from the cirques ceased is used within the cirques to meet evapo-transpiration and groundwater needs. None of this quantity is realized as runoff and must therefore be considered as lost to the usable runoff.
9. The calculated evapo-sublimation loss from the ridgeline deposit during the early melt period was approximately one-half the observed change in storage of the deposit. Here, the early melt period is defined as the time interval during which the main snowpack in the cirques was melting.
10. When the evapo-sublimation loss during the early melt period is combined with the quantity remaining in the ridgeline deposit after runoff has ceased, approximately 65 percent of the ridgeline deposit is not available for runoff from the cirques.
11. Based on these conclusions, any attempt to increase the size of the ridgeline cornice storage without a relocation of the deposit

will result in only minor changes in the observed runoff from the area.

12. The frequent summer showers common to the alpine study area had little or no effect on the runoff from the cirques. In only two instances, one during each of the two summer seasons, was there any indicated increase in runoff resulting from summer precipitation after the melt of the main snowpack was complete. The effect of rain on the melt of the snowpack in the cirques was not determined.
13. Approximately 75 percent of the water stored in the cirques at the end of the winter period was realized as runoff.
14. Based on these findings and the imposed constraints, a management technique consisting of the periodic removal of the ridgeline deposits with the snow being relocated in the cirques is believed to offer the greatest potential return.
15. In order to insure a high catch efficiency of the ridgeline deposits, the deposit should be removed whenever the primary separation zone becomes filled with deposited material.
16. A preliminary cost analysis suggests that approximately 240 acre feet of water per mile of ridgeline can be expected as increased runoff from the efficient application of this management technique. This water would have a cost of approximately $50 per acre foot discharged from the cirques.
17. Much additional work is necessary before a complete understanding of alpine snow hydrology and optimal management techniques are obtained.

V. REFERENCES

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Appendix I

Computer Listing of the Data Collected for 1973-1974.

EVAP. RATE (MM. OF WATER LOSS PER HOUR)	AVE.AIR TEMP. (DEGREES F.)	AVE.WIND VEL. M.P.H.	AVE.AIR VAPOR PRESS. INCHES OF HG.	AVE.VAPOR PRESS.GRAD. INCHES OF HG.	MONTH/DAY 1973-74	TIME OF DAY	SITE OF EVAP
-.02438	18.10	5.36	.04292	-.01746	12/14	MORNING	OPEN
-.01544	17.80	2.52	.05006	-.03332	12/14	MORNING	FOREST
-.03054	22.30	4.46	.04703	-.02742	12/14	AFTERNOON	OPEN
-.02443	21.00	2.23	.05067	-.03731	12/14	AFTERNOON	FOREST
-.08782	36.20	4.61	.05547	-.05753	12/20	AFTERNOON	OPEN
-.04582	35.25	2.17	.05536	-.08444	12/20	AFTERNOON	FOREST
-.05647	32.25	2.81	.03436	-.07974	12/20	NIGHT	OPEN
-.05413	32.00	5.36	.03679	-.09851	12/20	NIGHT	FOREST
-.02687	37.80	3.62	.09783	-.02767	12/21	MORNING	OPEN
-.03784	35.80	1.71	.08599	-.06971	12/21	MORNING	FOREST
-.06030	43.80	3.21	.09894	-.07416	12/21	AFTERNOON	OPEN
-.05471	41.40	1.60	.09022	-.09008	12/21	AFTERNOON	FOREST
-.01525	31.19	2.07	.03297	-.09853	12/21	NIGHT	OPEN
-.03018	29.43	.87	.06272	-.07518	12/21	NIGHT	FOREST
-.05222	34.80	5.19	.08563	-.06348	12/22	MORNING	OPEN
-.05385	33.20	2.54	.08016	-.05584	12/22	MORNING	FOREST
-.04887	41.20	2.46	.08693	-.08906	12/22	AFTERNOUN	OPEN
-.04541	37.60	.89	.07373	-.09077	12/22	AFTERNOON	FOREST
-.00180	23.86	.43	.06350	-.01168	12022	NIGHT	OPEN
-.00850	24.43	.03	.05913	-.05127	12/22	NIGHT	FOREST
-.01280	23.20	2.15	.08065	-.02064	12/23	MORNING	OPEN
-.01787	23.00	.84	.07632	-.03098	12/23	MORNING	FOREST
-.01226	19.10	3.70	.04098	.00006	01/03	AFTERNOON	OPEN
-.01022	15.30	1.44	.04471	-.01042	01/03	AFTERNOON	FOREST
-.01435	21.88	3.44	.07037	-.00727	01/09	AFTERNOON	OPEN
-.02197	21.62	1.76	.07151	-.02040	01/09	AFTERNOUN	FOREST
-.09576	20.43	9.27	.04763	-.02627	01/11	NIGHT	OPEN
-.07484	20.50	4.57	.05036	-.03120	01/11	NIGHT	FOREST
-.03315	28.25	7.22	.07412	-.03418	01/12	MORNING	OPEN
-.03277	27.42	3.63	.08048	-.03252	01/12	MORNING	FOREST
-.08941	27.62	8.79	.06366	-.04674	01/13	MORNING	OPEN
-.08357	30.25	4.72	.07399	-.04332	01/13	MORNING	FOREST
-.17539	35.35	8.73	.09755	-.03775	01/13	AFTERNOON	OPEN
-.18790	34.60	4.61	.04710	-.05080	01/13	AFTERNOON	FOREST
-.01953	26.75	6.07	.09208	-.01012	01/13	NIGHT	OPEN
-.02842	27.42	3.19	.08957	-.02233	01/13	NIGHT	FOREST
-.04343	29.92	6.36	.07260	-.03420	01/14	MORNING	OPEN
-.03219	30.25	3.07	.07374	-.04546	01/14	MORNING	FOREST
-.12224	42.33	8.73	.07670	-.07540	01/14	AFTERNOON	OPEN
-.10725	41.00	4.61	.09071	-.07529	01/14	AFTERNOON	FOREST
-.01229	25.00	2.04	.05346	-.00541	01/24	NIGHT	OPEN
-.01964	25.50	.88	.05839	-.03132	01/24	NIGHT	FOREST
-.02756	31.33	3.28	.05660	-.01896	01/25	MORNING	OPEN
-.03543	31.33	1.61	.06219	-.05141	01/25	MORNING	FOREST
-.05518	33.78	4.21	.07339	-.03031	01/25	AFTERNOON	OPEN
-.04959	33.10	2.79	.07526	-.05383	01/25	AFTERNOON	FOREST
-.00395	20.25	3.47	.06047	-.00189	01/25	NIGHT	OPEN
-.01303	20.82	1.88	.05949	-.02764	01/25	NIGHT	FOREST
-.01321	19.63	2.64	.06169	-.01653	01/26	MORNING	OPEN
-.01721	19.73	1.34	.06136	-.02662	01/26	MORNING	FOREST
-.03105	23.60	3.16	.05533	-.03032	01/26	AFTERNOON	OPEN
-.02730	23.15	1.69	.05530	-.04094	01/26	AFTERNOON	FOREST
-.00041	10.70	3.36	.04101	-.00121	01/26	NIGHT	OPEN
-.00800	11.47	1.55	.04214	-.01271	01/26	NIGHT	FOREST
-.01156	12.53	4.47	.03724	-.00080	01/27	MORNING	OPEN
-.01473	12.07	1.94	.03730	-.01839	01/27	MORNING	FOREST
-.03004	18.28	5.20	.03938	-.01716	01/27	AFTERNOON	OPEN
-.01645	17.50	2.45	.04328	-.02758	01/27	AFTERNOON	FOREST

Appendix I (continued)

-.00789	13.83	6.07	.04602	-.00326	01/27	NIGHT	OPEN
-.01738	13.93	3.12	.04492	-.01731	01/27	NIGHT	FOREST
-.02622	20.80	6.24	.04956	-.01112	01/28	MORNING	OPEN
-.02057	19.77	3.13	.05144	-.02833	01/28	MORNING	FOREST
-.04210	21.00	4.98	.05164	-.03297	01/28	AFTERNOON	OPEN
-.03061	20.27	3.00	.05280	-.03475	01/28	AFTERNOON	FOREST
-.01964	18.10	3.96	.04595	-.00285	02/02	MORNING	OPEN
-.01722	17.30	2.12	.04703	-.02208	02/02	MORNING	FOREST
-.10651	22.90	6.57	.04722	-.03100	02/02	AFTERNOON	OPEN
-.03404	22.25	2.96	.05659	-.03268	02/02	AFTERNOON	FOREST
-.01280	20.03	4.80	.06720	.00713	02/02	NIGHT	OPEN
-.01554	19.40	2.55	.07312	.00084	02/02	NIGHT	FOREST
-.02884	25.67	4.06	.06596	-.00247	02/03	MORNING	OPEN
-.02771	24.30	2.29	.06881	-.01705	02/03	MORNING	FOREST
-.05515	27.63	4.61	.05657	-.02971	02/03	AFTERNOON	OPEN
-.03703	26.67	2.29	.06350	-.03630	02/03	AFTERNOON	FOREST
-.03714	23.33	7.19	.05774	-.01933	02/03	NIGHT	OPEN
-.02166	23.80	3.86	.05519	-.03539	02/03	NIGHT	FOREST
-.12943	31.10	7.93	.04050	-.05954	02/04	MORNING	OPEN
-.11786	30.95	4.41	.04409	-.06496	02/04	MORNING	FOREST
-.10531	33.60	9.08	.05084	-.06056	02/04	AFTERNOON	OPEN
-.13152	33.20	5.08	.05768	-.06782	02/04	AFTERNOON	FOREST
-.08839	29.53	3.64	.04583	-.05787	02/22	AFTERNOON	OPEN
-.06175	28.10	1.76	.05817	-.05593	02/22	AFTERNOON	FOREST
-.12810	45.57	5.29	.09727	-.08303	03/01	AFTERNOON	OPEN
-.06523	44.63	2.38	.09601	-.08429	03/01	AFTERNOON	FOREST
-.05956	38.45	7.63	.07701	-.06279	03/01	NIGHT	OPEN
-.07936	38.70	4.30	.07439	-.08641	03/01	NIGHT	FOREST
-.05781	42.17	6.02	.09755	-.06175	03/02	MORNING	OPEN
-.05801	40.87	2.82	.09900	-.07090	03/02	MORNING	FOREST
-.10336	44.10	3.10	.06085	-.12031	03/08	AFTERNOON	OPEN
-.05570	43.83	1.33	.05830	-.12206	03/08	AFTERNOON	FOREST
-.01266	23.15	1.69	.08211	-.00760	03/08	NIGHT	OPEN
-.02262	23.75	.72	.08451	-.02589	03/08	NIGHT	FOREST
-.04722	29.87	2.04	.09992	-.00888	03/09	MORNING	OPEN
-.03129	30.57	1.02	.11618	-.01232	03/09	MORNING	FOREST
-.04171	36.30	2.55	.12644	-.05392	03/09	AFTERNOON	OPEN
-.03231	35.40	2.01	.12944	-.05092	03/09	AFTERNOON	FOREST
-.00851	25.67	1.15	.12341	-.01839	03/10	MORNING	OPEN
-.00686	26.13	.56	.12057	-.01993	03/10	MORNING	FOREST
-.05817	33.17	3.47	.09474	-.03436	03/11	MORNING	OPEN
-.03500	30.30	1.52	.09132	-.05508	03/11	MORNING	FOREST
-.14999	40.20	5.65	.11731	-.06305	03/11	AFTERNOON	OPEN
-.07645	39.20	2.92	.11979	-.06057	03/11	AFTERNOON	FOREST
-.13682	36.45	7.99	.08989	-.07231	03/29	AFTERNOON	OPEN
-.06967	35.30	5.44	.09048	-.07232	03/29	AFTERNOON	FOREST
-.10927	42.55	3.96	.08888	-.09142	04/05	AFTERNOON	OPEN
-.06253	42.50	2.20	.09331	-.08699	04/05	AFTERNOON	FOREST
-.02482	32.75	3.17	.08476	-.03724	04/05	NIGHT	OPEN
-.03708	32.55	1.59	.08648	-.05532	04/05	NIGHT	FOREST
-.11433	38.80	5.70	.08704	-.06226	04/06	MORNING	OPEN
-.08941	37.73	2.97	.09659	-.06561	04/06	MORNING	FOREST
-.11247	42.50	4.70	.08949	-.09881	04/06	AFTERNOON	OPEN
-.06492	41.25	2.61	.09601	-.08429	04/06	AFTERNOON	FOREST
-.09584	27.25	6.38	.06914	-.04276	04/07	MORNING	OPEN
-.05087	26.20	3.22	.07323	-.04988	04/07	MORNING	FOREST
-.10336	32.40	3.24	.06241	-.11069	04/10	MORNING	OPEN
-.05766	31.55	1.62	.07102	-.09738	04/10	MORNING	FOREST
-.00510	45.65	3.45	.06680	-.11349	04/17	MORNING	OPEN
-.00433	44.20	2.15	.07848	-.10182	04/17	MORNING	FOREST
-.01057	47.85	2.92	.07059	-.10971	04/17	AFTERNOON	OPEN
-.00562	43.30	1.66	.07081	-.10949	04/17	AFTERNOON	FOREST
-.00387	49.80	1.74	.08058	-.09972	04/18	AFTERNOON	OPEN
-.00235	47.55	1.17	.12489	-.05541	04/18	AFTERNOON	FOREST
-.00050	32.55	.16	.12417	-.03433	04/18	NIGHT	OPEN
-.00000	32.75	.01	.13440	-.02930	04/18	NIGHT	FOREST

APPENDIX I (continued)

-.00386	43.40	.79	.11580	-.05260	04/19	MORNING	OPEN
-.00283	42.30	.79	.12725	-.04195	04/19	MORNING	FOREST
-.00660	44.00	2.74	.10187	-.07843	04/19	AFTERNOON	OPEN
-.00345	43.05	1.00	.10736	-.07294	04/19	AFTERNOON	FOREST
-.09332	34.83	3.86	.09586	-.04924	04/20	MORNING	OPEN
-.05642	34.13	2.11	.10538	-.05542	04/20	MORNING	FOREST
-.07929	37.90	4.91	.11715	-.06315	04/20	AFTERNOON	OPEN
-.05669	36.70	2.94	.10848	-.07182	04/20	AFTERNOON	FOREST
-.06604	57.33	3.06	.08556	-.09474	04/24	AFTERNOON	OPEN
-.02428	53.30	.97	.10550	-.07480	04/24	AFTERNOON	FOREST
-.00737	57.00	.80	.12085	-.05945	04/25	AFTERNOON	OPEN
-.01504	53.20	.26	.15256	-.02774	04/25	AFTERNOON	FOREST
-.07648	47.60	4.92	.12389	-.05640	04/26	MORNING	OPEN
-.04844	46.87	2.32	.12864	-.05166	04/26	MORNING	FOREST
-.05519	53.80	3.41	.09194	-.08836	04/26	AFTERNOON	OPEN
-.02325	51.00	1.11	.09143	-.08887	04/26	AFTERNOON	FOREST
*.00000	.00	*00.00	.00000	-.00000	M WKZ	ĪA 6< AU	