Management of Windblown Apline Snows

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ABSTRACT OF THESIS

MANAGEMENT OF WINDBLOWN ALPINE SNOWS

The results of the study indicate that the runoff from alpine cirques can be successfully augmented by applying a management effort to the windblown snow deposits along the ridgeline. The technique investigated consisted of the periodic removal of the ridgeline snow deposits with the removed material being relocated in the cirques.

It was also demonstrated that through careful site selection it was possible to apply water-budget analyses to alpine conditions with the results of the analyses within acceptable error limits. These analyses were performed on; the data from the alpine region which serves as the supply or "feeder area" for the windblown ridgeline snow deposits, the data from one cirque on the leeward side which served as a control, and the data from an adjacent cirque to which the management effort was applied.

The water-budget analyses of the alpine feeder area indicated that nearly 80 per cent of the seasonal precipitation was transported out of the region by the end of the winter study period, 30 April. Only 23 per cent of this total transport (18% of seasonal precipitation) was caught in the natural cornice deposits along the ridgeline. In absolute measure, the transport was approximately 750 acre-feet of water from the 402 acre study area, while the cornice catch was approximately 172 acre-feet or 140 acre-feet of water per mile of ridgeline. The remaining 77 per cent of the transport is believed to have sublimated from both the in place snow cover in the alpine as well as during the transport over the ridgeline. There was no evidence of transport into the cirques beyond the limits of the cornice deposits, and no evidence of transport into the lower valley.

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 per cent of the water stored in the cirques during the winter period was realized as runoff during the melt period.

Based on these findings the previously mentioned management technique was suggested, tested under field conditions, and evaluated. The results of these studies indicate that an increase of approximately 240 acre-feet of runoff per mile of ridgeline treated can be expected from the efficient application of this technique. This increase will be the result of an increased catch efficiency of the ridgeline deposits as well as a reduction in the evaporative losses from the deposited snow. The increased runoff will have a cost of approximately $50 per acre-foot discharged from the cirques.

Many practical items concerning alpine conditions, cornice formation, blasting of snow, and management schemes are also presented in addition to the theoretical analyses.

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Chapter I

INTRODUCTION

The rapid increase in population as well as the per capita consumption of water during the past two decades has caused an ever increasing demand on many already overused water supplies. In some areas, these conditions have already resulted in water shortages. The shortage is especially critical in the Western United States which is experiencing an exceptionally large growth rate and yet suffer from water supplies already being used to capacity. In the area served by the Upper Colorado Basin, as well as adjoining watersheds with headwaters along the Continental Divide, it is readily apparent that the demand will soon exceed the supply. Realizing these conditions, the Colorado River Basin Act of 1968 specifies the obligation of the Bureau of Reclamation to develop early means of water augmentation.

The concept of augmentation by better production from existing water sources is one that only recently has received much attention. Efforts have ranged from such items as weather modification, aimed at increasing the precipitation over an area, to phreatophyte control, aimed at reducing the evapotranspiration losses during the transport of water from the source to the point of use. Much attention has also been given to the physical condition of the watershed and to management techniques which when applied to the natural system improve its efficiency of supplying useable runoff.

An examination of the water sources of the central Colorado Rockies reveals several important items. Grant, et al. (1968), noted that as much as 90 per cent of the total runoff from the area may be the direct result of melting snow which fell during the winter period at the higher elevations. It is also reported that a definite relationship between elevation and seasonal snow fall exists such that an increase in snow fall is expected with an increase in elevation, assuming all other factors being equal. Hjermstad (1970) sites this relationship as being 7.49 inches of increased water per 1000 feet increase in elevation for the area of the central Colorado Rockies lying between 7,000 feet and 10,600 feet m.s.l.

These conditions suggest that the greatest potential return per unit area from a management effort might be expected from winter or snow conditions at high elevations. When one considers that almost half (50,000 square miles) of the state of Colorado is located above an elevation of 10,000 feet m.s.l.,[1] it is apparent that the watershed with the greatest potential snow fall are located above timberline, which for the region is approximately 11,500 feet. The normal hydrometeorological data necessary for evaluating the efficiency of a management technique in such watersheds are not available. Thus any study of management techniques for the alpine region must also include as a major component a basic data collection system.

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[1] Yearbook of the State of Colorado 1962-64, State Planning Division, Denver, Colorado, pg. 622.

Purpose of the Study

The purpose and objectives of this study are:

1. Investigate the potential for applying management techniques to the alpine snow fields of the central Colorado Rocky Mountains for the purpose of augmenting the useable runoff.
2. If sufficient potential exists, indicate a management technique which could produce beneficial results under field conditions.
3. Evaluate the management technique under field conditions and suggest possible means of improvement.

These three objectives were aimed at answering two basic questions. Namely, is there sufficient water, as well as management opportunities, to warrant the development of an operational procedure? If there is, what technique suggests the greatest potential return. Associated with the second question is the ever present question of applicability under field conditions, or more precisely "can it be done?"

From both the objectives of this study and the preliminary remarks it can be seen that the orientation of the major effort was as much toward the "how to" type of questions as it was to the "why" or theoretical ones.

Scope of the Study

The findings presented are from a continuing study being conducted near the Continental Divide in central Colorado. A 450 acre area extending from timberline on the west, up onto the alpine ridge, and back down into two east facing cirques was instrumented for full hydrologic and meteorologic data collection (Fig. 1). Preliminary water-budget analyses for the ridgeline area indicated that a sizeable potential increase in runoff might occur through the application of a management effort. A technique consisting of periodic aritificially induced avalanches of the ridgeline cornice deposits was considered to offer the greatest potential return and was applied to one of the cirques while the second cirque was used as a control. The choice as to which cirque would be managed was determined by a randomized selection performed by an independent third person tossing a coin.

General weather conditions in the study area dictated the degree of management possible. The effect of the management effort on augmenting runoff was determined through the use of water-budget analyses applied to the various segments of the study area. The data from the study area was then compared to the historical records available at other locations in the general region as a check on the normality of the relatively short study period.

From these analyses a management technique was proposed and evaluated.

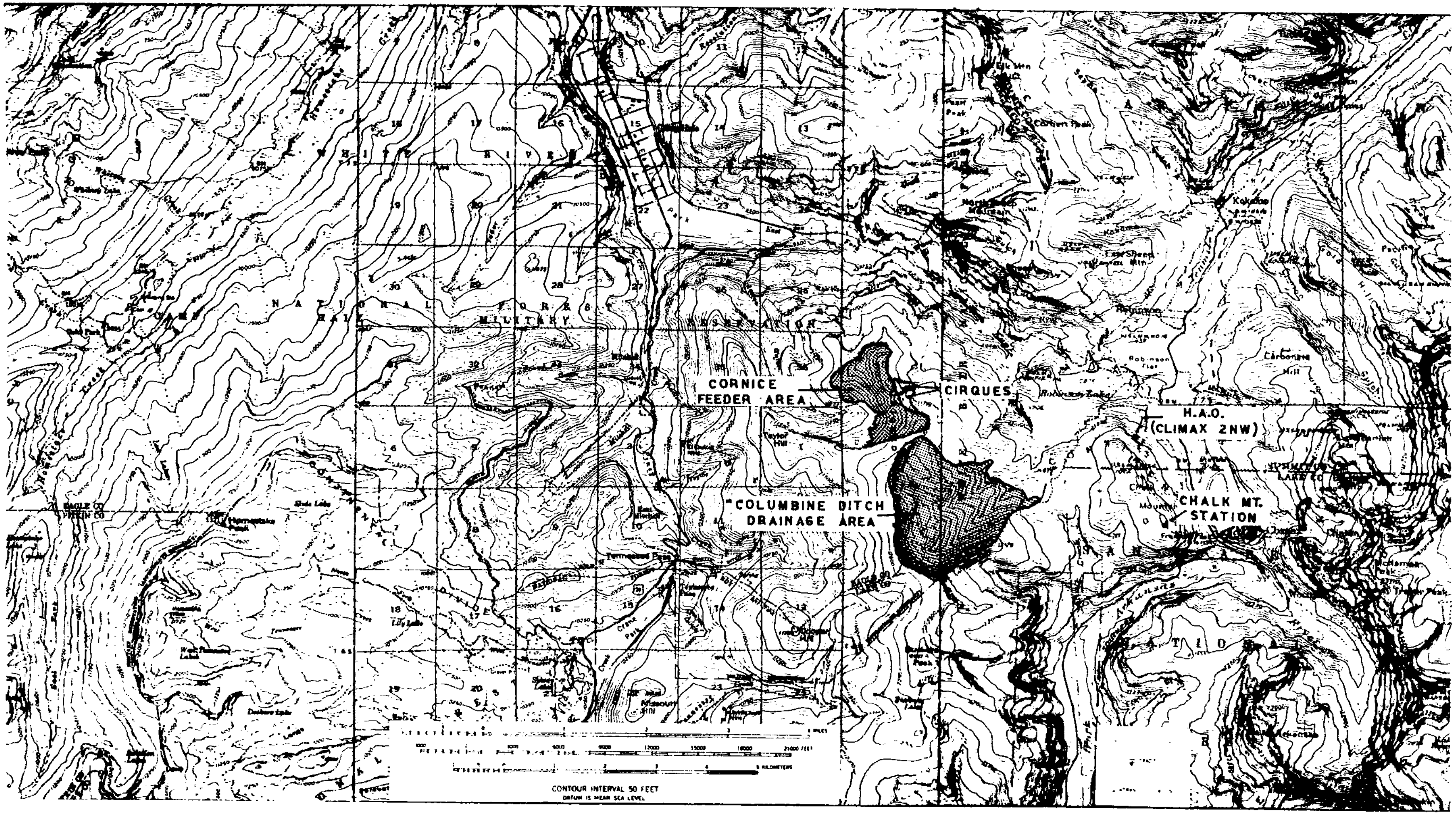

Fig. 1 Topographic map of the region encompassing the study area.

Chapter II

REVIEW OF LITERATURE

The problem under investigation is composed of many varied segments ranging from basic techniques discussed in elementary textbooks, to applications for which no record of previous study could be found. In view of the large number of items used in this study, the discussion here will be limited to the major items. For discussion of many of the basic techniques used in the hydrometeorologic analysis, the reader is referred to Chow (1964).

Management Techniques

The various watershed management techniques which have been applied to snow can be divided into four main categories: vegetation control, control of blowing snow, evaporation - sublimation control, and albedo modification. The first of these, i.e., vegetation control, has received the greatest amount of study at least in terms of management for the purpose of augmenting runoff. The main effect of such efforts has been an alteration of the snowpack accumulation over the watershed as well as a change in the melt rate resulting from a change in the net long wave and short wave radiation which reaches the snow surface. Anderson (1956) estimated that in the Central Sierras an increased accumulation of 12 inches greater than the surrounding forest could be obtained in clear cut areas of 20 acres or more. The snow melt from such areas, however, was much more rapid with the melt complete 10 to 30 days earlier than in the surrounding uncut forest. Similar results were obtained from other forest management techniques such as block cutting, strip cutting, and selective cutting, and have been reported by Anderson, Rice and West (1958), and Anderson and Gleason (1959). Although these early studies indicated an increase in the snow accumulation, the actual affect on the runoff was not indicated. The most recent opinion[2] concerning the effect of such operations on runoff is one of indecision. However, the general consensus is that in many instances the noted increase in accumulation is merely the result of a redistribution of the snow with only minor effects on the overall runoff.

Efforts in the control of blowing snow have been primarily directed toward protecting transportation facilities. There have, however, been several studies for augmenting runoff. Martinelli (1965) reported that by placing standard 4 foot high snow fences along the windward edge of natural snow accumulation areas in the Straight Creek region of the Colorado Rockies, the maximum water equivalent of the snowpack was more than doubled. Rasmussen (1969) in a study on the south end of Chicago Ridge near Climax, Colorado indicated that the deposit could be altered through the use of fencing, but not to the degree reported by Martinelli. Favorable results from the use of snow fences were also reported by Tabler (1971) on a study at Pole Mountain, Wyoming. Influenced by these and other results, the U. S. Forest Service has initiated an extensive study in the Lake Creek watershed

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[2] Symposium on Watersheds in Transition, Colorado State Univ., Fort Collins, Colo., June 1972. Proceedings to be available in late 1972 through Colorado State University and American Water Resources Association.

of the San Isable National Forest south of Independence Pass, Colorado. The preliminary results of this study indicate a small increase in the accumulation of the snow deposit on the leeward side of the fencing.[3] There is, however, no published statistical data yet available from this study.

The use of albedo modification as a management technique has, again, been primarily for purposes other than runoff augmentation. Several studies, such as Martinelli (1960) have been aimed primarily at runoff modification. A comprehensive literature review has been compiled by Slaughter (1966) and thus will not be repeated here. The reader is referred to this paper for a full evaluation of the technique.

The use of evaporation - sublimation control as a management technique has also been extensively reviewed by Slaughter (1970). Much controversy has been presented concerning the importance of evapo-sublimation from the snowpack with the major effort being concentrated on the melt period. The sublimation of blowing snow during the transport process has just recently received much attention. A study just completed by Schmidt (1972) indicates that losses during transport can be quite large and a mathematical model for predicting the magnitude of these losses is presented.

Snowpack Evapo-sublimation

The literature on the evapo-sublimation from the surface of a snowpack is extensively reviewed along the control techniques in the

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[3] "Potential of Save the Snow Project being Evaluated," The Herald Democrat, Leadville, Colorado, May 16, 1972, pg. 1.

paper by Slaughter (1970). Since the evapo-sublimation process is a major part of this presentation, a brief review is in order. The basic evaporation law was formulated by Dalton in 1834 and is of the form:

$$E = c\,(P_w - P_a)$$

in which

E = rate of evaporation, in./day

P_w = vapor pressure of the film of air next to the surface

P_a = vapor pressure of the air above the surface

c = coefficient dependent on barametric pressure, wind velocity, and "other variables."

Since the time of Dalton's formulation, numerous studies have been performed to evaluate the coefficient. These efforts have used such techniques as water-budgets, energy-budgets, and pan measurement to correlate the indicated evaporative losses to various measured meteorological parameters. The results from over 200 such studies are summarized in the paper by Slaughter (1970) and range from negligable quantities to more than 0.5 inches per day. Some of the studies have also indicated a negative loss or condensation onto the snowpack. Here again, a wide range of values have been reported. Garska, et al. (1958) and Martinelli (1960) observed condensation onto the snowpack in the central Rocky Mountains yet considered it negligable in terms of the seasonal water-budget. Studies in the Lake Superior region by Santeford, et al. (1972) have shown that the condensation onto the snowpack during the melt period is of the same order as the seasonal precipitation.

When one considers the results from the various studies, it is apparent that the indicated losses are highly dependent upon the local meteorologic conditions, and the major effort has been directed toward losses during the melt period and as such may not be representative of winter conditions.

Avalanching

Although numerous studies have been performed on avalanches and avalanching techniques, most of these have been for either safety purposes or protection of various structures and installations. No reference to the effect of avalanching on runoff could be found.

Due to the general purpose of most avalanche control, the general procedures employed are somewhat different than those employed in this study. Most control efforts are directed at avalanching the loose side hill deposit with the use of artillery or explosive charges placed on the side hill deposit. The cornice formation is generally far more stable and generally far more resistent to natural avalanches. As such, it offers a relatively small danger and has received only minor attention in terms of effective avalanching procedures. Some information is available in the paper by Mellor (1968) but is primarily concerned with the small formations as are encountered on ski slopes. Here, one small reference to the removal of cornices is made and consists of the use of 3 or 4, 1/2-pound sticks of 40% geletin placed approximately halfway down into the cornice deposit and at an interval of 6 to 8 feet parallel to the leading edge of the formation.

The blasting of snow, which was an integral part of the management technique investigated, is another area in which little information could be found in the literature. Some information, other than that presented above, is available in Mellor (1965b), yet the main application deals with work on artic snow fields.

When the various items which compose the major portion of this study are considered, it can be seen that many of the basic techniques and procedures have been developed by others and reviewed in the literature, yet their application to alpine conditions is not readily available.

Chapter III

POTENTIAL MANAGEMENT TECHNIQUES

In order to evaluate the applicability of various management techniques to alpine conditions, an understanding of the unique features of the area is necessary. The alpine is void of all larger forms of vegetal cover, with the only vegetation present limited to selected grasses and small surface plants. Severe weather conditions including strong winds, low temperatures and humidities, and maximum solar radiation are predominant. As a result, the area is often blown free of any appreciable snow cover and that snow which is not blown off is exposed to abnormally high evapo-sublimation losses.

Estimation of the Management Potential

Before consideration is given to the evaluation of various potential management techniques, it will be instructive to first consider from an order of magnitude computation the volume of water involved in the discussion. For comparison purposes the area which was selected as the primary study area will be used. It can be seen in Fig. 1 that the region has approximately one mile of ridgeline along which a cornice deposit forms. From the figures presented by Montagne (1968), it would be expected that from 50 to 75 acre-feet of water was stored in the cornice deposit. Assuming that one half of the area from timberline on the west to the ridgeline, approximately 400 acres, is blown free of snow and that the average snow fall is

18 inches of water equivalent, then there should be 300 acre-feet of water that was transported over the ridgeline. If there were only 50 to 75 acre-feet of water caught in the cornice deposit, the remaining 200 or so acre-feet of water needs to be accounted for.

Further insight into the magnitude of the volume of water which might be available for potential management is obtained from the historical record of runoff from the Columbine Ditch, a transmountain diversion located just to the south of the study area (Fig. 1). Using the winter precipitation data from the High Altitude Observatory[4] as a base index, the precipitation-runoff relationship of Fig. 2-A is obtained. In part B of this figure the frequency distribution of the runoff coefficient, so computed, is shown. At first consideration, it might appear that a major portion of the available water is accounted for in the measured runoff from the ditch. However, when the potential feeder area for the ditch is considered, i.e., the area to the west of the ditch drainage extending from the ridge down to timberline on the west, along with the transport across the ridgeline it can be seen that, in general, less than one-third of the potential is realized as runoff. When the difference in precipitation between the ridgeline and the HAO station is considered, the value of one-third is reduced even more.

From these preliminary values it would appear that there is considerable transport from the feeder area, yet the transport is not apparent in the runoff from the leeward side of the divide.

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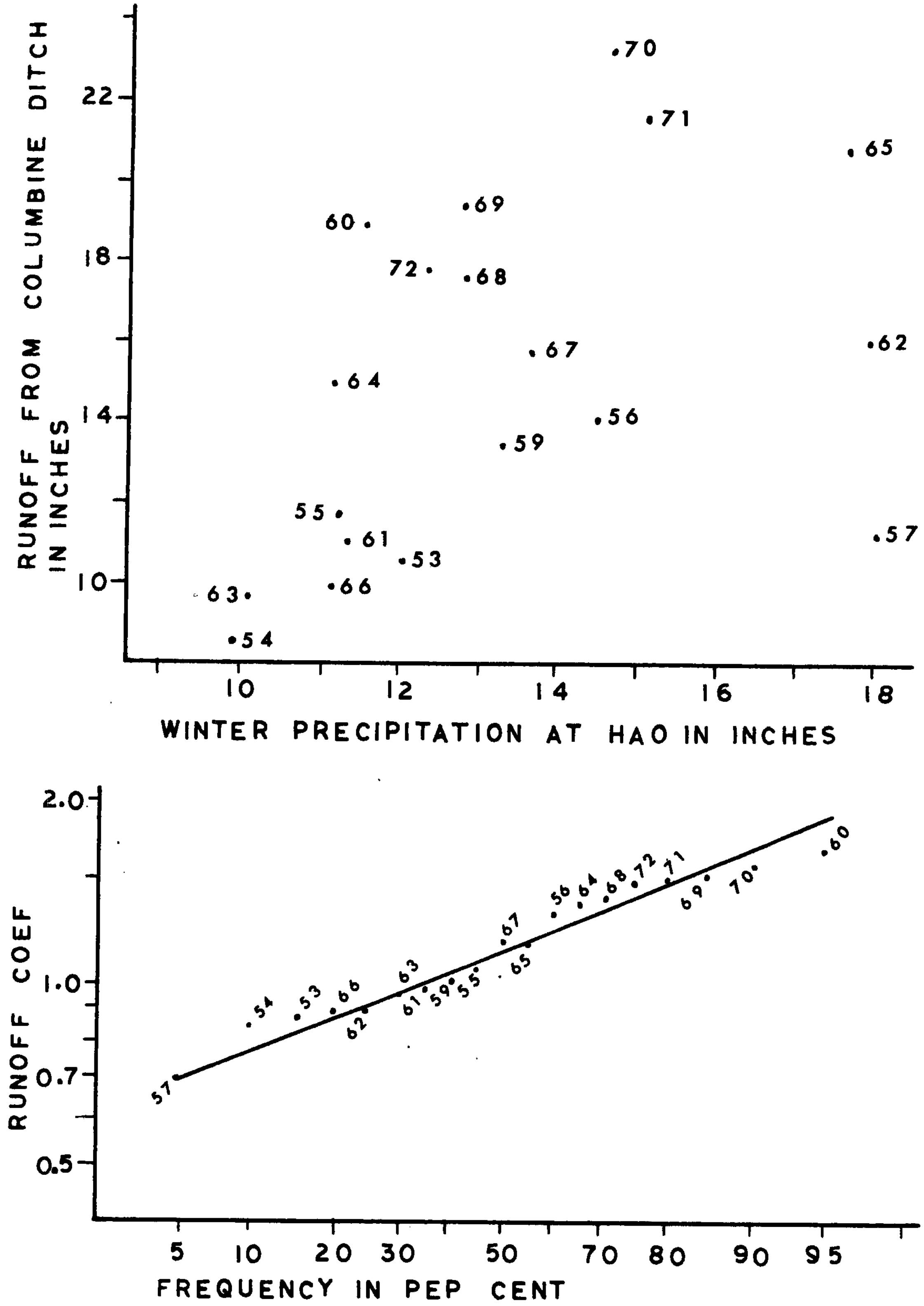
[4] This station has a USWB designation of Climax 2NW. However, to be consistent with other C.S.U. publications it will subsequently be referred to HAO.



NOTE: The numbers adjacent to the plotted points are the year of the various runoff seasons.

Fig. 2 (A) Winter precipitation at HAO vs. runoff from the Columbine Ditch; (B) Frequency distribution of the above precipitation vs. runoff relationship.

Furthermore, if this transport is occurring and actually leaving the area, is there a means by which the transport can be reduced and thus increase the runoff from the study area.

The discussion thus far has considered only a very small area near Climax, Colorado. If it is assumed that the values used in the previous consideration are representative of the alpine regions in the entire state, a much better indication of the magnitude of the quantity involved can be obtained. No reliable measure of the size of the alpine region in the state could be located. However, by using the published official figures[5] of 50,000 square miles above 10,000 feet m.s.l. and consulting the U.S.G.S. topographic maps for the state, an estimated 10,000 square miles are located above timberline in the state of Colorado. Using a value of 18 inches for the seasonal precipitation, and assuming one half is blown off the area and lost, the losses from the state represent approximately 4,800,000 acre-feet and is more than half the seasonal flow of the Colorado River at Lee's Ferry, Arizona (9,000,000 acre-feet).[6]

Potential Management Techniques

The unique nature of the alpine make many of the conventional management techniques not applicable. For example, all techniques which rely on the use of vegeltal management to affect the accumulation of snow are not applicable as there is no vegetation to which the control could be applied. The use of evapo-sublimation control applied to the main snow cover is also believed to be questionable. The work

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[5] Yearbook of the State of Colorado.

[6] Grant (1968), p. 67.

by Slaughter (1966) and Essington and Smith (1967) with the use of monofilms to retard the evaporative losses from the general snow pack indicate that in order to be effective a new monofilm layer must be applied after each new snow fall. Using the winter precipitation record at HAO (November through April) Chappell (1967) found that 80 per cent of the time the daily precipitation was within the range of 0.04 to 0.40 inches and 99 per cent of the time it was from 0.02 to 0.65 inches. When the differences between the HAO site and the alpine region are considered, it can be seen that to apply a monofilm layer to the general snow cover during the entire winter period would require nearly a daily application. The cost of such an effort would be prohibitive. The limited application of such an effort to the late winter snow pack, or even to just the wind blown deposits along the ridgeline, might prove feasible. However, there would be no effect on winter losses.

The use of albedo modification on the entire alpine snow pack is also believed to be questionable. The limited application to the major snow accumulation regions would affect the timing of the melt and possibly increase the runoff from these deposits by decreasing the time of the melt and thus the overall losses. There would, however, be no effect on the amount of snow transported out of the area during the winter period and thus have only minor effects on the seasonal water-budget.

It would appear that the major potential for management is with the control of the transported snow from the alpine region. The use of such items as fencing to increase the snow accumulation and thus reduce the transport from the ridgeline has several objections.

In order to hold any type of fencing in the alpine, strong supports and tie downs are needed to withstand the forces imposed by the strong winds. Such installations are "unsightly" in the eyes of the public and as such are often considered infeasible for other than technical reasons. The increased snow deposited behind such structures is deposited at or near the ridgeline and thus exposed to the strong winds, low humidities, and high solar radiation associated with the alpine. These meteorologic factors can contribute to high evaporative losses such that during the melt period for this increased accumulation, the evaporative losses may be of the same order as the increased water equivalent of the deposit.

It was believed that the greatest potential for an effective management effort was with a system that could meet the following constraints:

1. Be efficient at catching the transported snow blown out of the feeder area.
2. Relocate the deposited snow in an area removed from the high evapo-sublimation potential associated with the ridgeline conditions.
3. Rely on a minimum amount of physical alterations or structural equipment which might result in unpleasant astetic view.
4. Be independent of the use of any substance, chemical or otherwise, which might be detrimental to the environment.

The Technique Investigated

The choice of artificial induced avalanches as the technique to investigate in this study evolved from simple observation of alpine conditions. Discussions with Bob Rinker,[7] Professor L. O. Grant, and others indicated that during the early winter the rate of change in the size of the ridgeline cornice deposits was very apparent. Yet, after about mid-winter the rapid growth of the cornice appeared to be much less. If, however, a piece of the cornice should for some reason break-off, the resulting void was quickly filled while the undisturbed cornice remained relatively unchanged. The avalanched piece of cornice material along with some of the snow from the lower slope was deposited in the cirque on the leeward side, removed from the area of strong winds and possibly shaded from some of the direct solar radiation. As a result of the change in environment, the deposited material could be in an area of reduced evapo-sublimation potential.

It was believed that similar results could be obtained through the use of induced avalanching of the ridgeline deposits. By systematically removing the deposits, it was believed that the size of the deposit could be kept relatively small and thus the rapid growth noted with the natural deposits during their early development might continue for a much longer period. The material removed from the ridgeline deposits by the avalanching effort would be relocated in the cirques, and possibly in an area of reduced evapo-sublimation potential. The use of this technique relied on the natural efficiency of the ridge to form separation zones and subsequent deposition of snow. No alterations or structures were needed. Since the only foreign material used was the explosive charge needed to induce the avalanche, it was

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[7] Technician in charge of the field operation for the various C.S.U. Department of Atmospheric Science projects centered in the Leadville region.

believed that the effect on the local ecology would be minimal. Thus, all of the constraints considered necessary for an effective management technique could be met to some degree by this procedure. This is not to imply that the procedure used was optimal, but rather that it is a feasible solution within the imposed constraints.

Chapter IV

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 Fig. 1 was selected. This primary 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

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

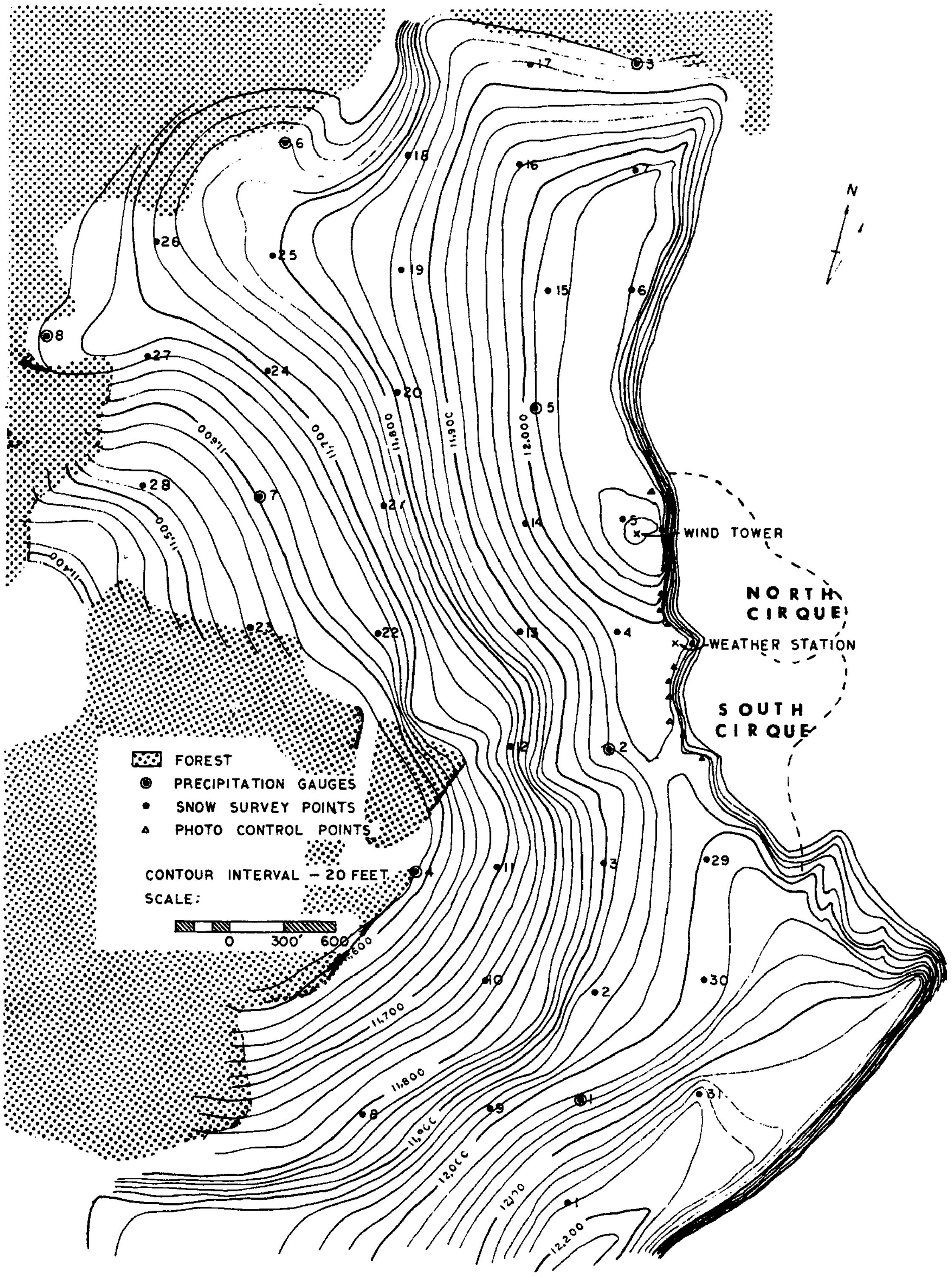


Fig. 3 Topographic map of the alpine feeder area.

support only sparce vegetation. During the winter this ridgeline area is generally blown free of any appreciable snow cover.

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 gages number 4 and 7 as shown in Fig. 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 Cirques

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 Fig. 4 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.

Each of the cirques has a considerable amount of exposed bedrock with the north consisting mainly of igneous formations while the south is completely sedimentary (Fig. 5). When the topographic features of Fig. 4 and the surface geology of Fig. 5 are combined with data on the

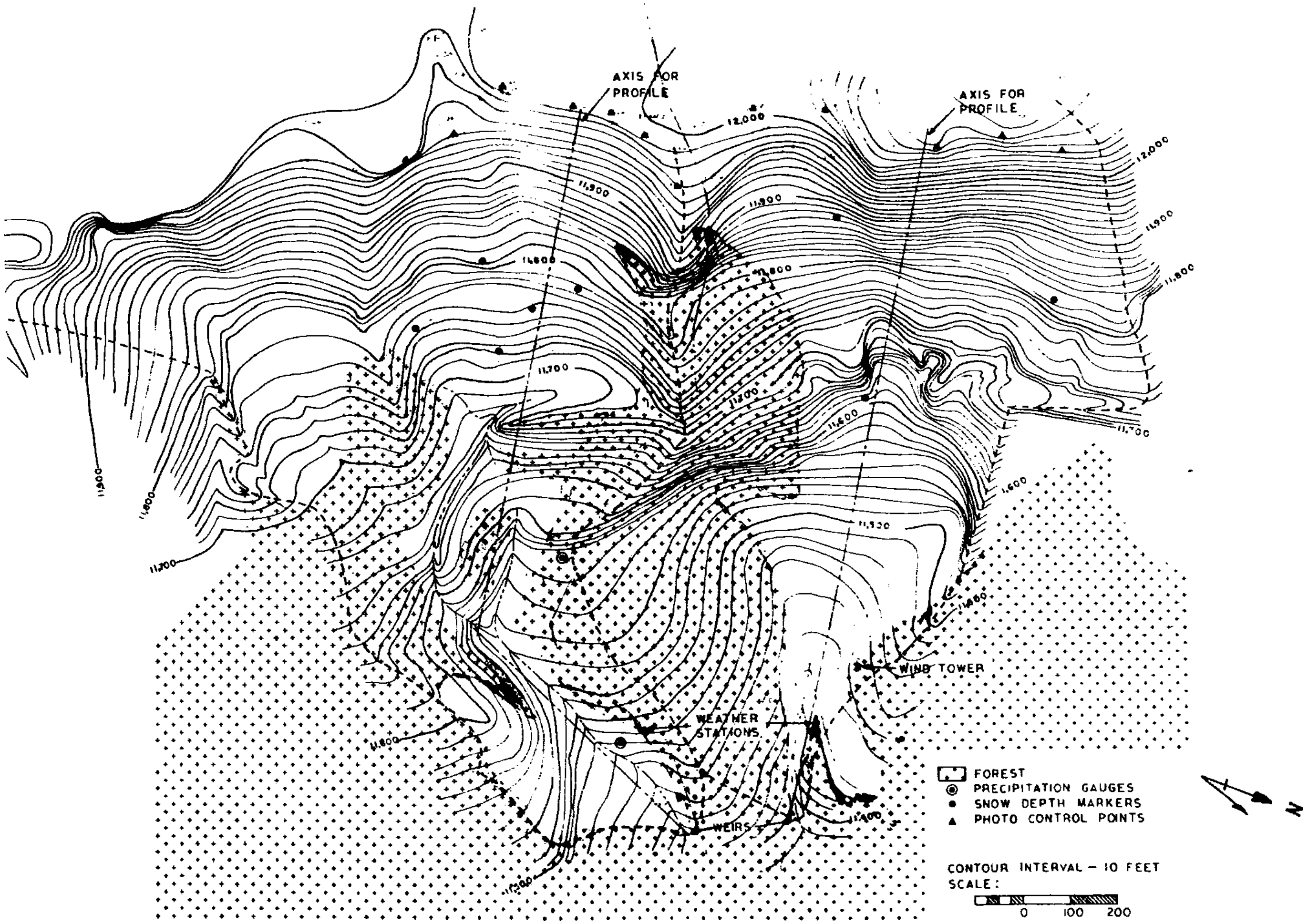


Fig. 4 Topographic map of the cirques.

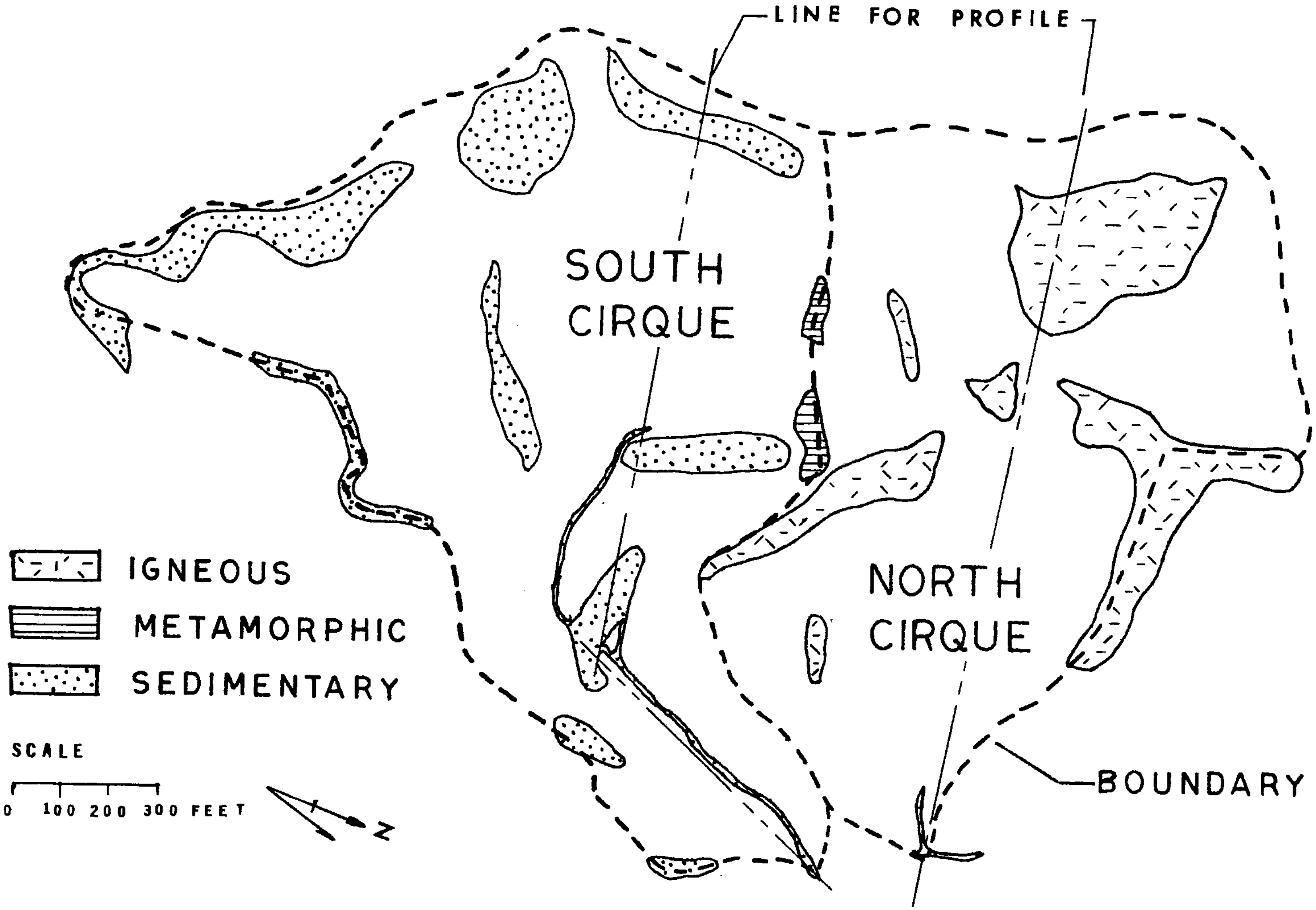
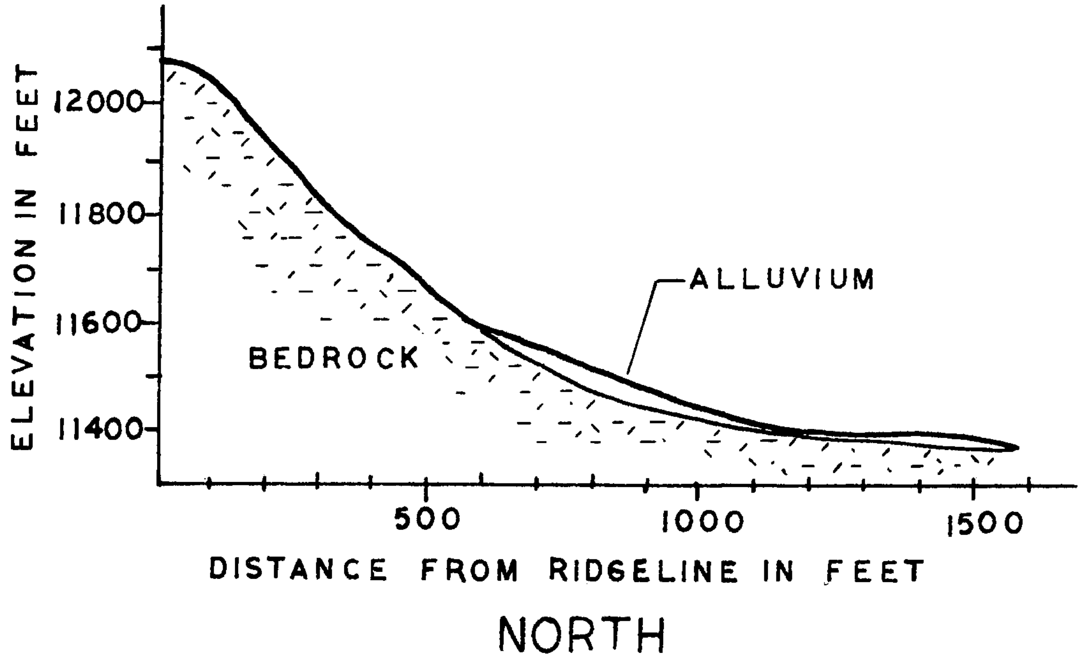


Fig. 5 Surface outcroppings in the cirques.

thickness of the surface mantel, the profiles of the general geologic formations can be obtained and are shown in Fig. 6. The profiles of both cirques are along the sections indicated in Fig. 4 and 5. Although variations exist along various other sections, the profiles shown are believed to be representative of the area. From these figures it can be seen that each of the cirques is underlined by bedrock and much of the boundary is formed by rock outcroppings. The entire length of the watercourse on the south cirque is carved into the bedrock which is the same formation as that exposed at the ridgeline. The same condition is observed on the north cirque, however the stream length is much shorter with the headwaters originating at the base of the alluvial deposit. A short distance downstream of the weirs on each of the cirques a sudden increase in the slope of the ground occurs. Below this region the first existence of any appreciable depth of soil mantel is encountered. In the intervening area, i.e., downstream of the weirs for several hundred feet, no springs or other evidence of ground water seepage could be detected.



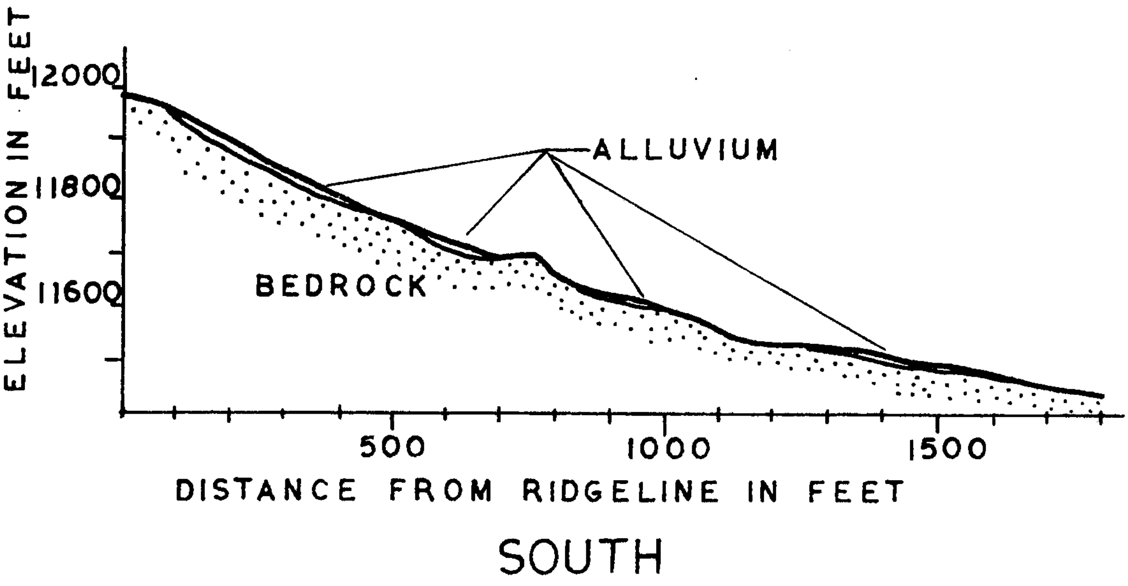


Fig. 6 Representative profiles for the cirques. The indicated profiles are along the lines shown in Fig. 4 & 5

Chapter V

PROCEDURES AND INSTRUMENTATION

The evaluation of the effect of the artificial avalanching on augmenting runoff from the cirques involved a complete hydrometeorologic analysis of the study area. The data were collected and evaluated with the intent of establishing a water-budget for the various components of the study area and thus determining the amount of water transported from the feeder area as well as the probable destination of this migratory quantity. The data collection was hampered somewhat by severe weather conditions which, on occasion, resulted in a breakdown of the primary system. In such cases, estimates of the missing data were obtained from secondary systems such as regressions with similar stations and auxiliary measurements. Unless specifically stated otherwise, standard instruments and data reduction techniques were used.

Water-budget in the Feeder Area

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

$$\text{inflow} = \text{outflow} + \text{change in storage}$$

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 gages equipped with unbridled Atler shields placed at selected locations within a network of 39 snow sampling stations. At each precipitation gage snow survey data were also obtained. The location of each of these stations can be seen in Fig. 3. 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 believed to be representative of the actual conditions. Therefore isohyetal maps of the snow pack water equivalent were constructed encompassing all available data ranging from topographic features to field observations of drift patterns.

The catch efficiency of the precipitation gages 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-windslab deposit, and the direct transport of blown snow from the feeder area into the cirque. The last two terms, i.e., the cornice-windslab 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 gages located at the points indicated on the map of Fig. 4. As a check on the efficiency of these gages, 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 snow pack 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 per cent of the cirque area was not surveyed. However, nearly 70 per cent 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 simply 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 full development of this procedure has been included in Appendix A.

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 snow pack. 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 snow pack 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 into 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 measurement. The appropriate value for the transport can be obtained from the previous considerations. The fallout 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. file 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. For a full discussion on the use of replicators see Hindman and Rinker (1967). 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 snow pack 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 the general location of HAO (Fig. 1).

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.

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, backfilling, 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 considerable between the different avalanche events. A full discussion of the detailed procedure along with the success and difficulties encountered with each event is presented in Appendix B.

The effect of the avalanching as a management technique was determined utilizing much of the data previously discussed. The over-all 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 snow pack in the cirques and the losses from the ridgeline deposits are in proportion 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.

Chapter VI

OBSERVATIONS ON CORNICE DEVELOPMENT

The development of the cornice deposit under actual field conditions is a highly complex system influenced primarily by meteorologic and topographic factors. Although a detailed analysis of the formation process is beyond the scope of this study, certain observations on the behavior of the deposits in the general location of the study area are informative in understanding the data analysis which follows in the next chapter. The behavioral patterns associated with the various types of cornice deposits become extremely important in designing and evaluating a management technique aimed at their control for the purpose of augmenting runoff. This discussion is based on numerous field observations of the actual snow transport as well as studies utilizing colored smoke and zero-lift balloons as tracers in the air flow patterns. For safety reasons, no observations were made when the average hourly wind speed was in excess of approximately 35 mph. Most of the observations were made when the wind speed was less than 20 mph.

Throughout much of the discussion reference will be made to work performed by Montagne, et al. (1968) concerning the nature and control of cornice deposits. The first portion of Montagne's paper which deals with the formation process associated with the cornice deposits on the Bridger Range in southwestern Montana has been included for easy reference as Appendix C.

Physical Characteristics of the Deposit

The wind blown deposits on the leeward side of the ridge, often referred to as cornice deposits, are composed of various parts and are not all true cornice formations. The sketch of Fig. 7 represents one type of deposit common to the study area. The nomenclature used is that common to field personnel and differs somewhat from that used in the technical literature on cornices. However, since this study is orientated toward the practical application of a technique, it is believed that this choice of nomenclature is the more appropriate one. The division of the deposit into its various parts, indicated by changes in physical properties, is somewhat arbitrary and is presented merely as an aid to the discussion. Under field conditions, the boundaries between the various parts are sometimes hard to define and actually consist of a transition zone and not a distinct separation.

The deposit shown in Fig. 7 is often divided into two parts; the cornice, or ridgeline deposit, and the windslab, or sidehill deposit, which forms immediately below the cornice. The ridgeline deposit may be further subdivided into the actual cornice, or overhang, and the deposit behind the cornice. In addition to these various portions of the ridgeline deposit, Fig. 7 also shows the location of several critical points which will be used repeatedly throughout the subsequent discussion.

One of the distinguishing features of the windslab and the upper portion of the ridgeline deposit is that a variable density with depth, or a layering condition, is often encountered. This layering is believed to be the result of alternate deposits of natural snowfall and wind blown material, with the latter being characterized by small

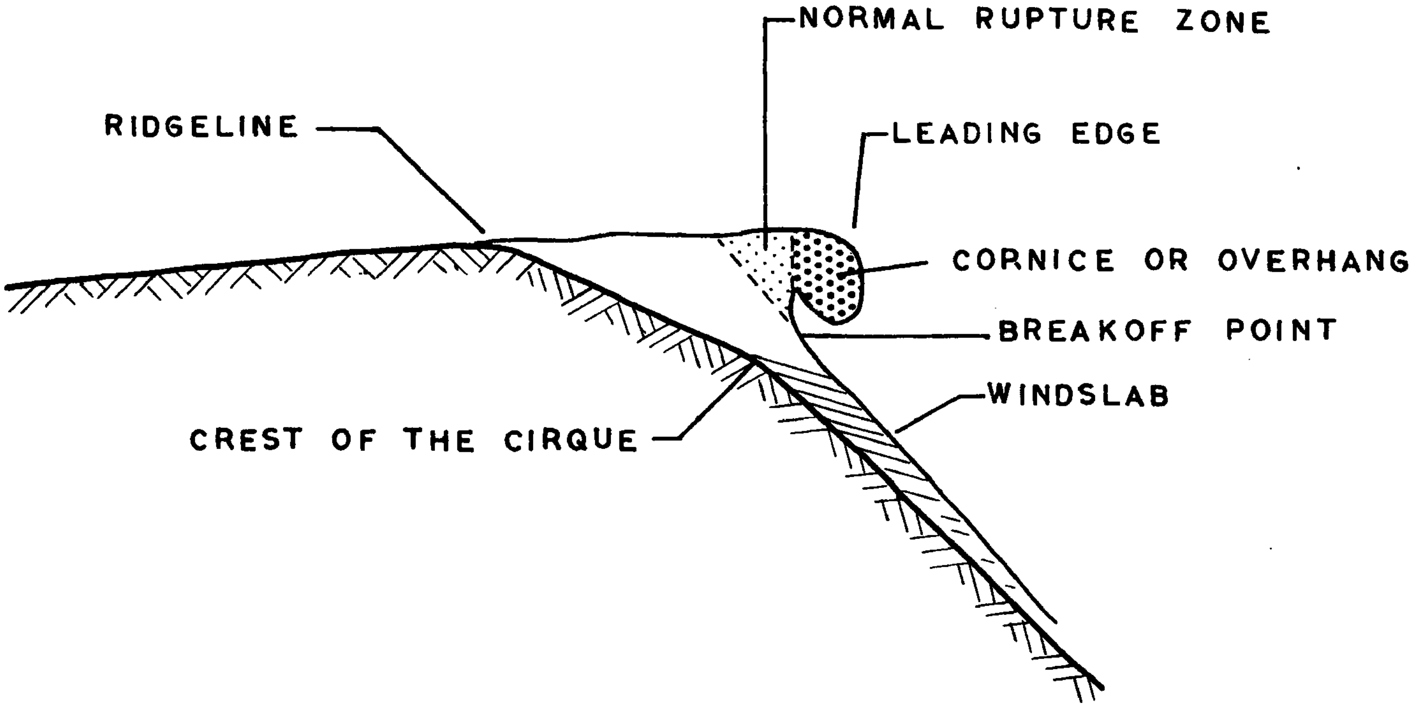


Fig. 7 Sketch of the cornice formation depicting the location of the various items and terminology used.

fractured particles having a highly compact structure. The deposits resulting from the natural snowfall have, in general, much larger particles with less fracturing and a much less compact structure.

The actual cornice, or overhang, does not show this layering condition, but rather has a much more uniform density. Very little change in the size of the individual particles, in comparison to the change noted in the other parts of the deposit, is seen and the entire formation has a highly compact structure. These physical features, which might seem insignificant, are believed to be the result of the deposition process and are highly influential in determining the efficiency of the artificial avalanching effort.

Expected Airflow Over the Ridge

The expected airflow over the ridge and encompassing an isolated cirque is shown in Fig. 8. The distinguishing features of this circulation are a general expansion and downward circulation on the leeward side of the ridge with a reversal of the flow in the lower reaches. This reversal results in a general upslope condition in the cirque area. Near the crest of the cirque a reversal of the flow direction is again encountered defining the limiting boundary of the primary circulation. With this airflow pattern, snow deposits are expected in the separation zones near the ridgeline and at the base of the circulation in the lower valley. Such deposits would be the result of pure sedimentation caused by the fall velocity of the snow

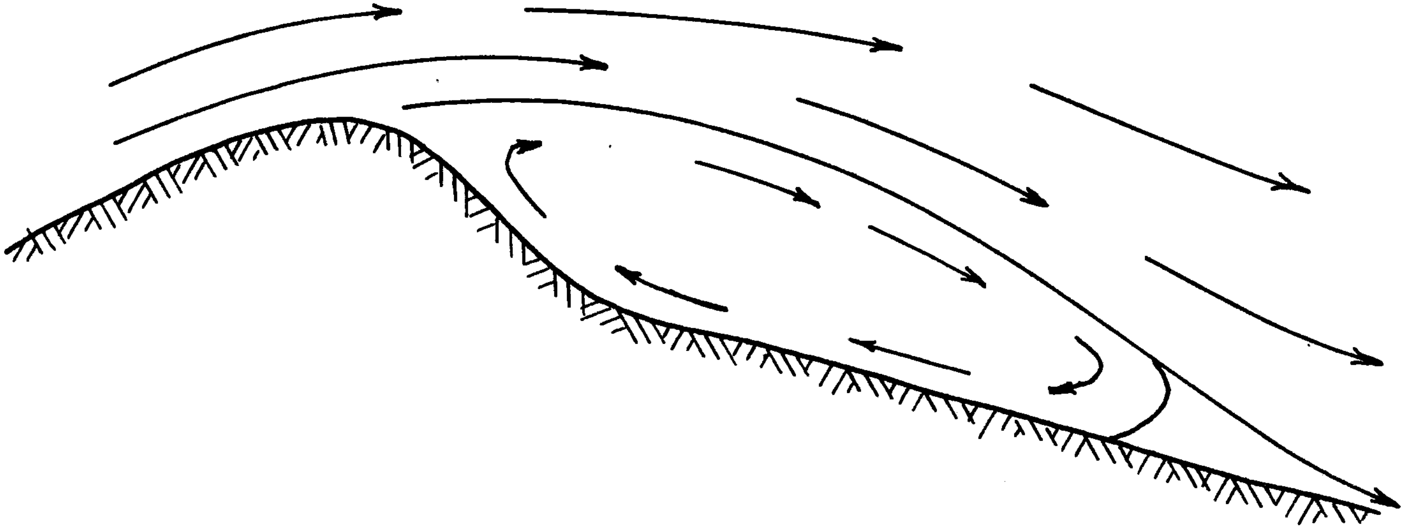


Fig. 8 Schematic diagram of the primary circulation.

particles, and as such should have a density[8] of from 10 to 20 per cent. Since the observed density of the ridgeline deposit was approximately 57 per cent, the theory of deposition as a result of pure sedimentation does not fully explain the observed conditions.

Observer Airflow

The observed flow consisted of two parts, the primary circulation as noted in Fig. 8 and a secondary circulation consisting of an eddy formation in the vicinity of the leading edge of the cornice. A photograph of the observed airflow indicated by the use of colored smoke as a tracer is shown in Fig. 9. Here, it can be seen that the main flow is basically straight out from the leading edge of the deposit. Within about 150 to 200 feet of the deposit the effect of the turbulence becomes so great that the smoke is totally dissipated and the remainder of the flow pattern is not indicated. With the natural snow transport, a characteristic plume of snow is often seen to resemble the same pattern as indicated with the smoke in Fig. 9. The natural snow, as well as the smoke, often gives the appearance of an upward motion a short distance downwind of the cornice deposit. This apparent upward motion is believed to be the result of the wavelike nature of the separation zone formed along the boundary between the primary circulation and the ambient flow. Under periods of high transport from the ridgeline, and thus high velocity flow, the

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[8] The definition of the density of snow is different from the normal use of the word "density." The definition used is the ratio between the volume of the water equivalent of sample and the volume of the sample. This ratio is often reported as a decimal, in gr./cc., and as a percentage. The latter will be used here.

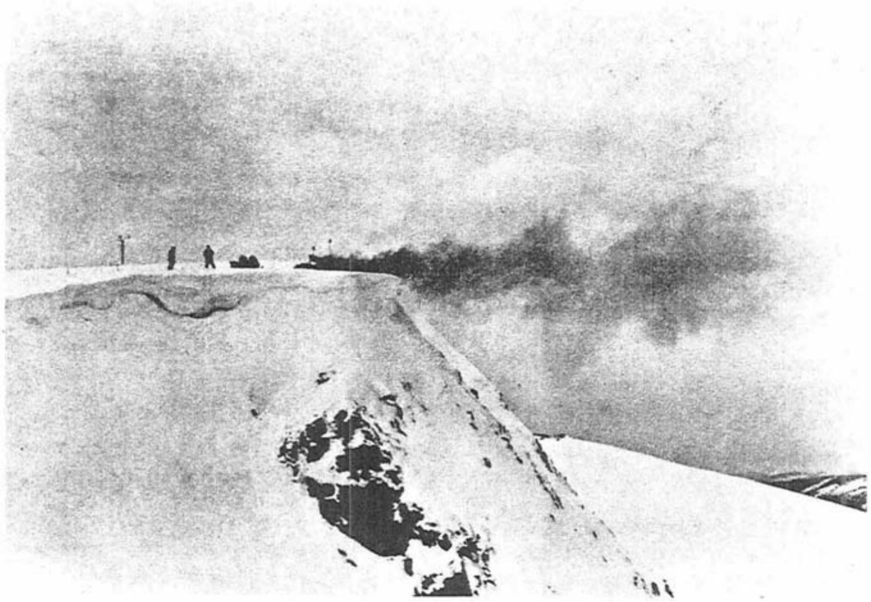

Fig. 9 Photograph of the colored smoke tracer indicating the observed airflow in the vicinity of the leading edge of the deposit.

transported snow is quickly dissipated in the air field immediately downwind of the cornice deposit. With the fluctuating nature of the boundary between the two flows, as well as the general turbulence in the region, the plume of transported snow is often swept in an upward direction as it leaves the ridgeline. Since the snow is quickly dissipated once it leaves the ridge, the subsequent downward fluctuation in the flow is not readily apparent and can result in an improper conclusion of the existence of an upward circulation. It should be remembered that the flow is not constant, and is continually fluctuating in both speed and direction. These fluctuations in flow velocity result in additional fluctuations in the plume of transported snow.

When the size of the circulation is considered, it can be seen that due to the large scale factor there is no Reynolds Number effect on the flow. With this condition, the same flow pattern must exist under all values of ambient wind speed. Due to the three dimensional nature of the flow, changes in wind direction can, and do, cause changes in secondary flows. The primary circulation, however, remains basically unchanged. This condition of no Reynolds Number effect due to the large scale factor implies that the flow patterns observed under light to moderate wind conditions are the same as those for the high wind speeds, and thus limited observations can be used to define the flow patterns under all wind speeds.

In addition to the primary circulation, a secondary circulation consisting of a roller or eddy just under the leading edge of the cornice was observed at many locations along the ridge. The occurrence of this roller type circulation was limited to those areas where a distinct cornice, or overhang, deposit existed. In those areas where the secondary circulation was not apparent, a large drift type formation without the distinct overhang was noted. In this secondary circulation, a lateral motion parallel to the leading edge of the formation was always present in addition to the rotational movement. Furthermore, this lateral motion was noted to be of a constant direction and did not appear to fluctuate with time as did the turbulent eddies associated with the primary circulation. Although on all observations the direction of the lateral motion was the same, it is possible that under certain wind directions, not observed, the direction could be reversed.

Observations on the limiting velocity necessary to bring about visible transport in the feeder area indicated that once transport was observed, the secondary circulation was also apparent. For the winter period, this condition of incipient motion was noted at a wind speed of approximately 12 mph. The primary circulation, however, was not visually apparent until the wind speed was at least 18 mph. This is not to imply that the circulations did not exist at lower velocities, but rather that there was not sufficient transport to make the circulations visually apparent at these lower wind speeds. If colored smoke or some other tracer wereused, the circulations could be detected at these lower wind speeds. With increases in the ambient wind speed, the amount of snow carried into the primary circulation with its characteristic plume of blowing snow appeared to increase while the amount carried by the secondary circulation appeared to remain almost unchanged.

Development of the Cornice Formation

The mechanisms which result in the cornice formation are not fully understood and are generally beyond the scope of this study. There are, however, several observations which appear to be somewhat different than the findings presented by Montagne, et al. (1968)[9] and thus are worth noting. There are considerable differences in the topographic features between the Bridger Range where Montagne performed his studies and Chicago Ridge where this study was performed. As will be seen shortly, the changes in topographic features along Chicago Ridge within the study area had a significant effect on the shape of the deposit. Thus it may be that the differences in topographic features causes the apparent differences in the formation process noted between the two studies.

The process proposed by Montagne is basically one of adhesion of the particles followed by sintering. He notes the existence of stellar snow flakes which have a mechanical interlocking to account for the adhesion process as well as saltating grains for which the adhesion process is still unknown.

The observations on Chicago Ridge indicate basically the same results except that the existence of stellar snow flakes is highly unlikely in any of the transport material. Examination of the upper surface of the deposits indicated the existence of small highly fractured particles with no evidence of a single flake observed. The existence of stellars and thus growth similar to that described by

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[9] As noted previously the portion of this paper which deals with the formation processes has been included as Appendix C.

Montagne is possible during the precipitation periods. However, these are not the periods during which the major availability of snow and thus the major growth are believed to occur.

One process, not mentioned by Montagne, which is believed to be important in increasing the water content of the deposit is that resulting from the constant fluctuation in the wind. These fluctuations cause a constant pounding effect on the surface of the snow which is believed to further compact the structure aiding in the development of the layering conditions observed on the upper portion of the ridgeline deposit as well as the windslab. This process is believed to be particularly important during periods of strong winds when it was observed that little change in the size of the cornice occurred, yet an increase in density as well as a sizeable increase in the windslab were measured. As mentioned previously, the occurrence of the secondary circulation is also believed to be important in the formation process even though Montagne's work indicates that the velocities are too small to be an important factor. The constant co-existence of the secondary circulation and the overhang formation suggests that the two are related and influence the overall formation of the deposit.

When consideration is given to the management of the deposit for the purpose of augmenting runoff, it can be seen that four stages in the development of the formation are important regardless of the intricate mechanisms which brought about the actual formation. The relative importance of these stages is affected by the local topographic features of the individual site location and will be apparent from the subsequent discussion. Consideration will first be given to the most general case with the modifications imposed by the local topography considered separately. The ridgeline deposits will be classified according to the nature of their upper surface and designated as upslope, neutral, and downslope deposits. The distinction being made is in regard to the relative elevation of the leading edge of the formation with respect to the ridgeline. For example, if the leading edge of the mature deposit is higher than the ridgeline, the deposit would be classified as upslope. If the deposit has a distinct overhang, it will be classified as a cornice. If no overhang exists, it will be referred to as a drift formation. Thus there can be upslope, neutral and downslope cornices as well as upslope, neutral, and downslope drifts. One further distinguishing feature, the relative separation between the ridgeline and the crest of the cirque, will be treated separately without any distinct classification.

A schematic drawing of the subsequent stages of development of an upslope cornice is shown in Fig. 10. Part A shows the initial deposition which occurs in the separation zone just downwind of the ridgeline. This initial deposit is primarily the result of pure sedimentation and as such does not generally exhibit the relatively high density common to the remainder of the deposit. With increased size, the upper surface of the deposit approaches the boundary of the separation zone and is exposed to the pulsating effect of the flow which tends to compact the overall structure. During this stage of development, i.e., between that shown in Fig. 10A and 10B, the water content of the formation can increase greatly with only minor changes in the overall size of the deposit. Once the deposit reaches the size shown in Fig. 10B, the secondary circulation becomes apparent and the

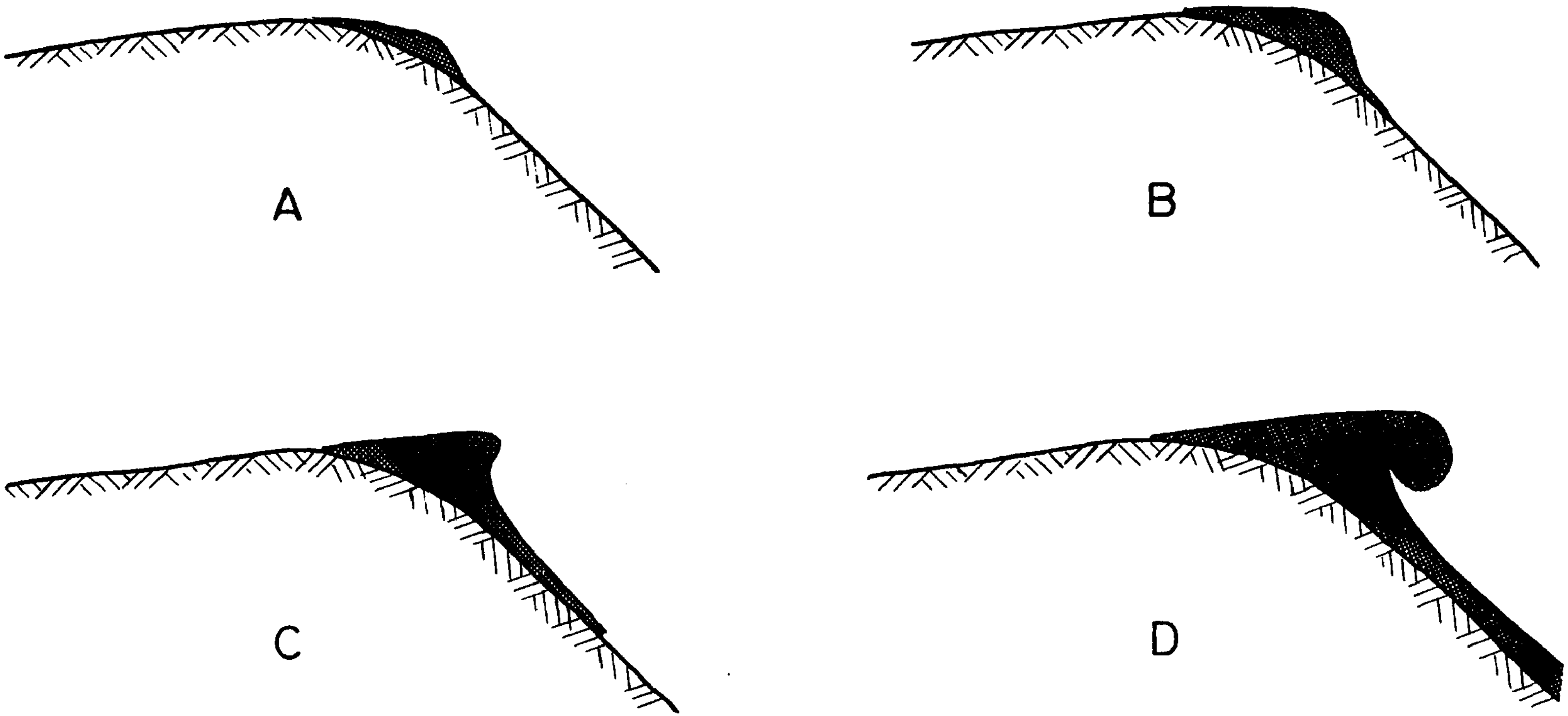


Fig. 10 Schematic diagram showing the various stages of development of the cornice formation: (A) initial deposition; (B) growth in the separation zone; (C) initial cornice formation; and (D) the mature deposit.

overhang begins to form, Fig. 10C. The formation continues to grow at a decreasing rate until the mature formation of Fig. 10D is reached. This upper limit to the size of the formation is not a fixed quantity, but rather is constantly changing with changes in the general airflow. These changes in the mature cornice are much smaller than those which occurred during the early stages of development. They may, however, have a distinct effect on the management effort.

During periods of light to moderate transport from the feeder area, large changes in the size of the overhang on the immature cornice were seen to occur. During such conditions, the plume of transported snow leaving the ridgeline was generally not apparent and very little change in the windslab formation was seen. As the transport rate increases, there appears to be a point beyond which the rate of growth of the cornice decreases. Under conditions of high transport, and thus large plumes of transported material leaving the ridge, the overhang was often seen to remain the same size and even decrease in size even though large amounts of material were available for the growth processes. The windslab, however, was seen to increase drastically during these periods of high transport often filling the space between the windslab and the overhang. If the overall formation was still in the immature stage, and sufficient wind conditions exist, a large overhang again formed. If, however, the mature deposit existed at the time when the strong wind were encountered and the separation between the windslab and cornice filled, only a minor overhang developed during the remaining season. It should be remembered that there is a definite limit imposed by the circulation patterns beyond which deposition does not occur. Once this limit is reached, errosion occurs at a rate equal to the deposition, and the growth ceases.

The various stages of development with the neutral and downslope cornices are basically the same as those for the upslope cornice. There is, however, one additional characteristic associated with the downslope cornice formations in the study area which is believed to be the result of the controlling airflow. At all locations along the ridgeline, there is some cross-section which has a predominant influence on the airflow approaching the ridgeline at that location. This cross-section will be referred to as the "controlling cross-section" as it is influencing the approaching airflow as well as the resulting deposit. If this controlling cross-section is such that the general airflow in a region has a downward component as it crosses the ridgeline, a downslope deposit will result. Such a configuration is shown in Fig. 11. With this condition, both the cornice and drift type formations were observed with the latter being limited to those areas where the secondary circulation was not apparent. When the secondary circulation and thus the overhang was present, a soft slab deposit located on the sidehill just below the windslab was also present. This soft slab is subject to frequent natural avalanches and is the only type of formation for which any evidence of natural avalanching could be detected during the two year period. During the 1971-72 season, evidence of 7 natural avalanches was seen along the nearly three miles of ridge visible from the access route leading to the cirques of the study area. All of these were of the soft slab type on sidehills beneath downslope cornices. These soft slab deposits are believed to be the result of snow particles settling on the slope

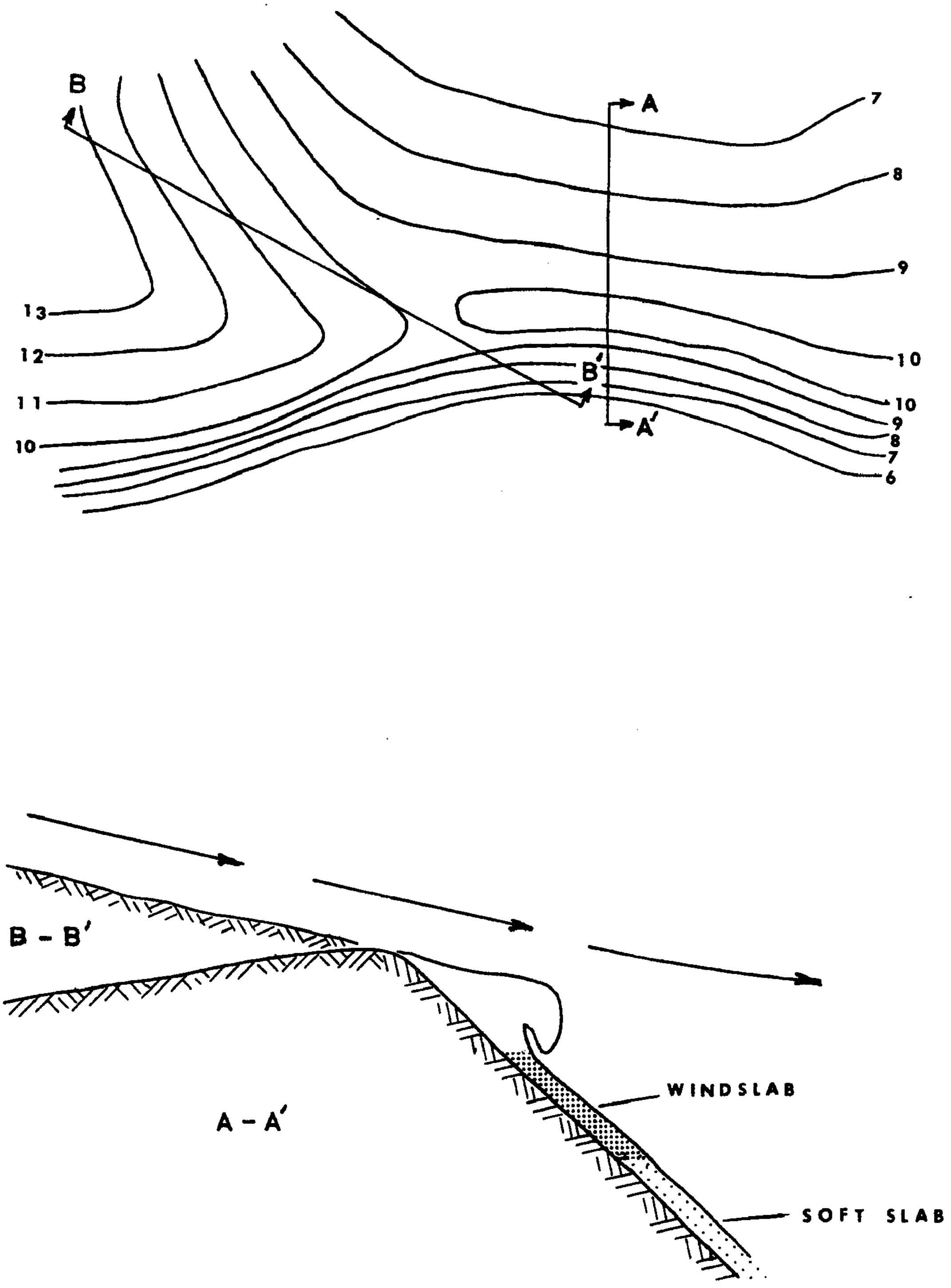


Fig. 11 Schematic diagram showing the major items associated with the downslope cornice formation: (A) plan view; (B) profile view. Section B-B' is the controlling cross-section. The affect of the coincidence of the ridgeline and the crest of the cirque on the shape of the deposit is also shown.

after overshooting the limits of the secondary circulation. With the upslope cornice, the tendency to overshoot the secondary circulation is not as great and thus the occurrence of the soft slab is not as predominant.

Effects of the Deposit on the Management Effort

The management scheme investigated was one which required a cornice formation. The basic procedure consisted of blasting off large pieces of cornice, having them fall onto the windslab, and hopefully having enough impact to release the windslab and trigger a sidehill avalanche. With this scheme, a relatively large overhang in comparison to the size of the windslab is necessary for effective removal. If a period of strong winds was encountered and the space between the windslab and cornice became filled, a very dense deposit with a nearly vertical face occurred. If a subsequent cornice formed, it was basically ineffective at removing the windslab on subsequent management efforts. When the new cornice was removed, it fell onto this very steep surface and merely slid off without causing much affect on the windslab. Thus the volume of water stored in the removed cornice was the only portion relocated in the cirque.

The relative distance between the ridgeline and the crest of the cirque was also very important in determining the degree of success obtained from the management effort. In Fig. 7 it can be seen that when the ridgeline and crest of the cirque are separated by a sizeable distance a large portion of the deposit is resting on a relatively mild slope and as such cannot be removed by the technique investigated. At one location in the study area, over 70 per cent of the deposit was in this condition and could not be effectively managed by the technique utilized.

The drift type formation offers still another unique situation in terms of the management effort. When attempts were made to remove the drift by blasting, the upper front portion was removed while the lower portion along the leading face of the formation remained in place forming a ledge type cross-section.

As noted previously, the north cirque was chosen as the one to manage while the south served as a control. The north cirque has no downslope cornices and thus no experience with this type of formation was encountered.

The comments presented in this section are not intended to imply that it is only the upslope cornice with a large overhang in comparison to the size of the windslab that can be effectively managed. The technique investigated is most effective for this type of cornice. For other types of deposits, some other technique may be better suited. However, in order to evaluate these various techniques, a basic understanding of the physical nature of the deposits is essential. For comparative purposes, the classification of the deposits in the study area are shown in Fig. 12.

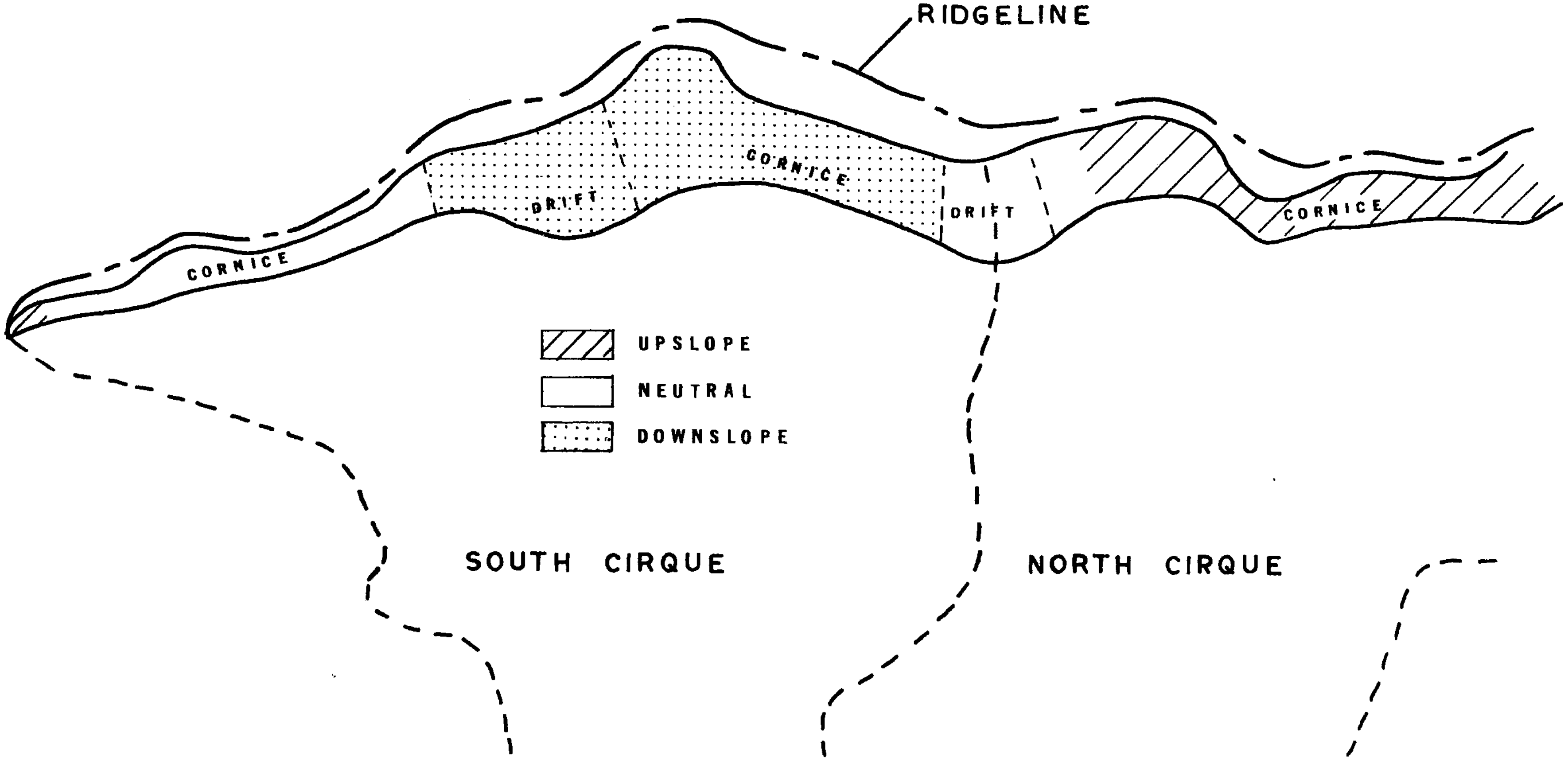


Fig. 12 Classification of the ridgeline deposits in the study area as they existed near the end of April 1972.

Chapter VII

ANALYSIS OF THE DATA

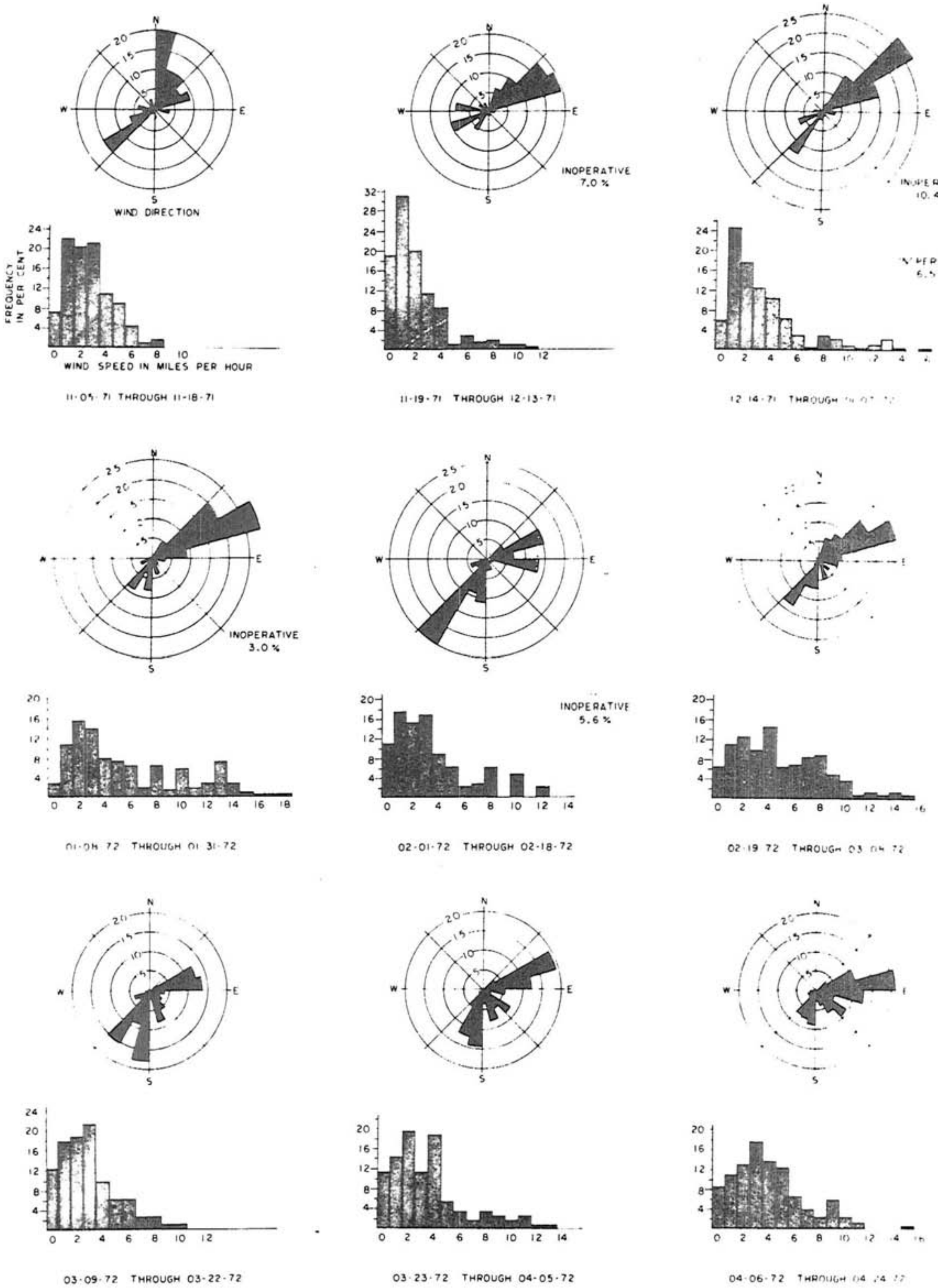
The format used in Chapter V, Procedures and Instrumentation, might suggest that the analysis was performed on various sets of data. Although there are various sub-sets to the data, it is basically one set oriented toward answering the question of what effect the avalanching had on the runoff from the study area.

Similarity of the Two Cirques

The hygrothermograph data for each of the cirques was reduced by finding the average readings for each 3 hour period with divisions made at 3, 6, 9, 12, 15, 18, and 24 hours. An analysis of variance with subgroups was then performed to test the similarity of both the temperature and absolute humidity values with groupings of the data on a daily, weekly, and monthly basis. In all but five such groupings over the two year study period, the null hypothesis H_o: the subpopularion means are the same, had to be accepted at the 95 per cent confidence level. Thus it would appear that there is no significant difference between the two cirques with respect to temperature and absolute humidity.

During the 1970-71 season, wind data were collected in both cirques. When an analysis of variance similar to that performed on the hygrothermograph data was performed on the average hourly wind data, it was again seen that no significant difference could be detected between the average wind data for the two cirques. However, when the instantaneous values of wind direction as recorded in each of the cirques were compared, the null hypothesis as stated above could not be accepted at even the 80 per cent level. Further analysis indicated that there was no apparent correlation between the instantaneous wind direction in the two cirques. If, however, the analysis was limited to wind speeds in excess of 10 mph, the instantaneous wind direction as recorded in the two cirques were within 10 degrees of one another 90 per cent of the time. This condition is not the normal case and, as will be seen later, the wind speed in the cirques was rarely observed over 10 mph. It may therefore be concluded that there is no apparent difference between the average hourly wind data for the two cirques, yet at the same time there is no apparent correlation between the instantaneous direction as recorded in the two cirques. Based on these findings, as well as prior committments for the equipment, the wind recorder on the south cirque was removed at the end of the 1970-71 season. All wind data presented for the cirques during the 1971-72 season are those as recorded in the north cirque. The frequency distribution for 1971-72 data is shown in Fig. 13.

The precipitation data from the three precipitation gages located in the cirques are listed in Table 1. It can be seen that the values for the three gages are generally quite close to one another and there is no systematic variation that would suggest a local influence on any one of the gages. Thus it will be assumed that the mean of the three readings is a reasonable estimate of the precipitation. On six separate occasions during the 1971-72 season, snow survey samples were taken in the immediate vicinity of each of the gages. On all occasions the difference between the water equivalent of the snow pack



NOTE: The axes on all graphs are as indicated on the one in the upper left position.

Fig. 13 Frequency distributions of the wind speed and direction in the north cirque for the various sub-periods, 1971-72 season.

TABLE 1

Precipitation Data for the Cirques

(All Data are the Indicated Change in the Gage Storage From the Time of the Previous Reading in Inches)

	North	South			
Date	Lower	Upper	Lower	Mean	Error*
2-01-71	0.00	0.00	0.00	0.00	±.00
2-08-71	.10	.05	.20	.12	.03
2-15-71	.90	1.08	.85	.95	.05
2-22-71	.75	.62	.69	.69	.03
3-01-71	.25	.13	.19	.19	.02
3-08-71	.56	.62	.62	.60	.01
3-15-71	.19	.31	.19	.23	.03
3-29-71	.19	.19	tipped over being repaired	.37	.00
4-23-71	1.34	1.57	1.48	1.46	.05
5-14-71	.00	.00	.00	.00	.00
5-28-71	.56	.56	.53	.55	.01
6-14-71	.40	.43	.46	.43	.01
6-28-71	.33	.25	.31	.30	.01
7-13-71	.25	.25	.25	.25	.00
7-27-71	.45	.50	.40	.45	.02
8-16-71	.30	.30	.25	.28	.01
END OF 1970-71 SEASON					
11-05-71	.00	.00	.00	.00	.00
11-10-71	.00	.00	.00	.00	.00
11-26-71	.69	.69	.69	.69	.00

TABLE 1 - Continued

Date	North	South		Mean	Error*
	Lower	Upper	Lower		
12-02-71	1.18	.75	.95	.96	.09
12-15-71	.44	.50	.47	.47	.01
12-31-71	1.56	1.50	1.43	1.50	.01
1-06-72	.87	.75	.87	.83	.03
1-14-72	.50	1.00	.81	.77	.14
1-27-72	.88	1.00	tipped over returned to service	.94	.05
2-03-72	.38	.25		.32	.05
2-18-72	1.00	1.00	.94	.98	.01
2-24-72	.37	.50	.44	.44	.03
3-09-72	1.40	1.40	1.50	1.43	.02
4-14-72	.81	.75	.75	.77	±.01
4-28-72	1.04	1.00	1.10	1.05	.02
DATE OF SNOW SURVEYS IN CIRQUES					
Winter Totals	12.25	12.40	N.A.	12.31	±.19
5-12-72	1.00	.93	.93	.95	.02
5-31-72	.70	.70	.65	.68	.01
6-12-72	.10	.10	.08	.09	.01
6-27-72	.13	.16	.15	.15	.01
7-04-72	.38	.42	.42	.41	.01
7-21-72	.19	.19	.14	.17	.01
7-28-72	.10	.10	.08	.09	.01
END OF 1971-72 SEASON					

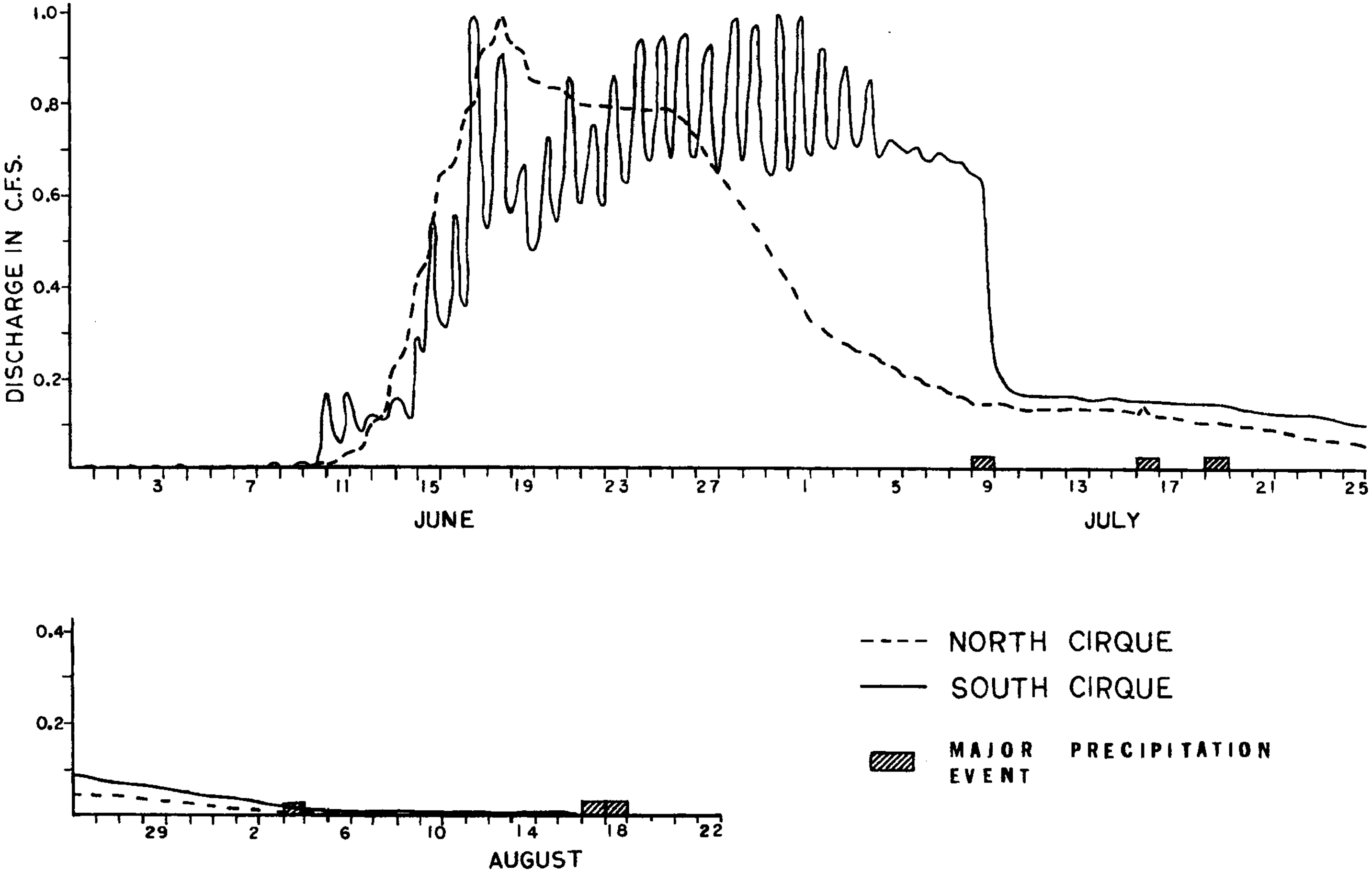
TABLE 1 - Continued

Date	North Lower	South Upper	Lower	Mean	Error*
Interium Totals	2.60	2.60	2.45	2.45	±.03
Seasonal Totals	14.85	15.00	N.A.	14.85	±.21

*Standard error of the mean of the three readings.

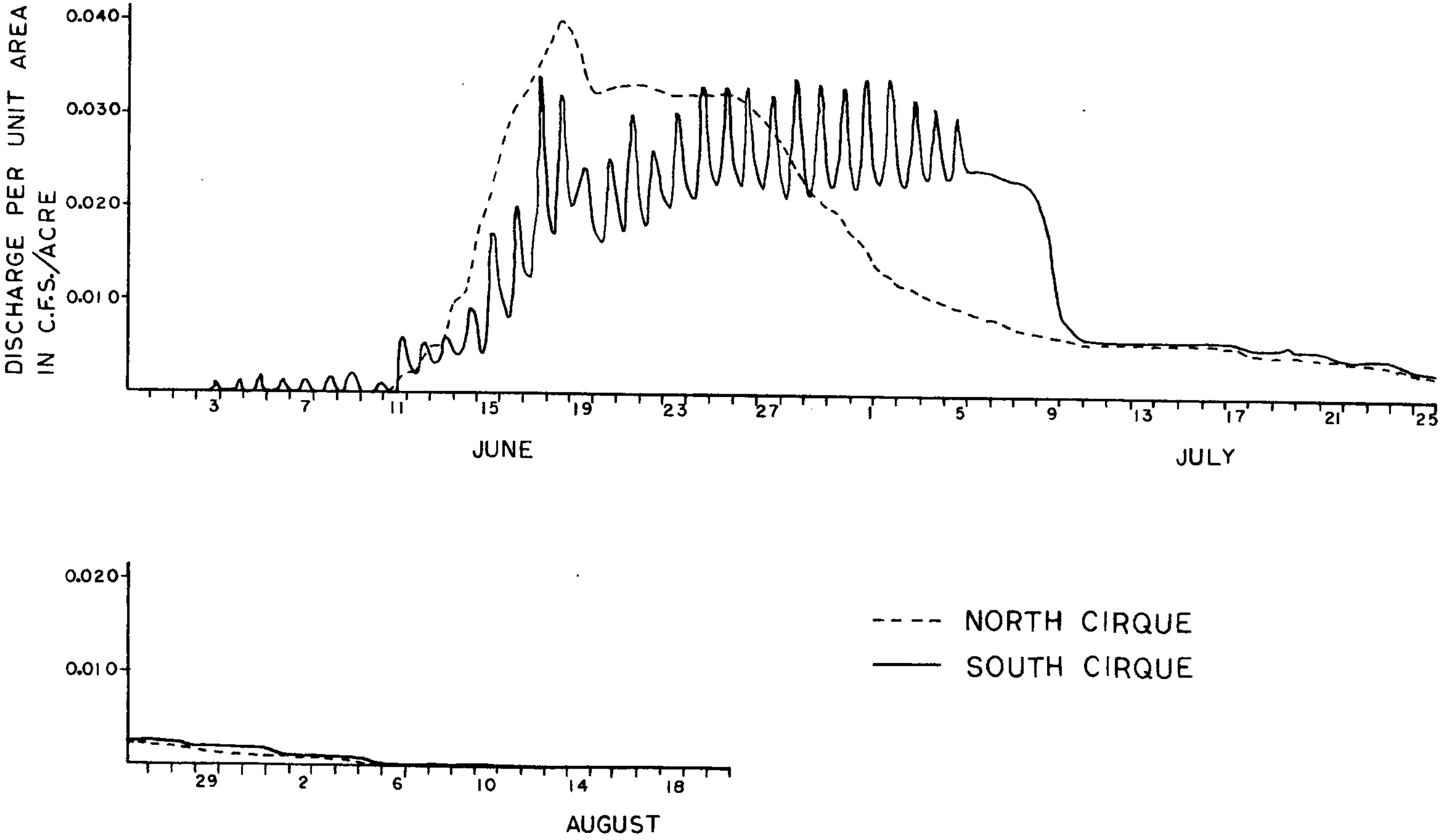
and the cumulative precipitation as recorded by the gage was within the accuracy of the snow survey measurements, i.e., 0.25 inches. Thus it will be assumed that the standard error of the mean as computed for the three precipitation gage readings is representative of the error associated with the mean value.

In the description of the study area, it was stated that the area of the south cirque was approximately 25 per cent larger than that of the north, yet the ridgeline was almost 180 per cent longer. Considering this additional potential cornice area, one might suspect that the runoff per unit area on the south would be much larger than that on the north. The data for the 1970-71 season showed that this was not the case. In Fig. 14 the hydrographs for the 1970-71 season are shown. Here it can be seen that the flow on the south cirque started 9 days before that on the north, yet they both stopped on the same day, 17 August. The flow on the south is also seen to be much more variable than that on the north with this difference believed to be due primarily to the differences in geology and exposure. The north cirque has a large alluvial deposit which acts as a reservoir for the melt water dampening out much of the daily fluctuations. Also, the north cirque has a much greater portion exposed to the direct solar radiation which results in a more rapid melt near the beginning of the runoff period and an earlier decline as the melt became limited to the wooded areas. When the actual flowrate is reduced to flow per unit area, the graphs of Fig. 15 result. Here again, the same differences are seen. Once the main snow pack had melted, the flow per unit area on the two cirques which resulted primarily from the melt of the remaining cornice deposit was almost identical. The



NOTE: The ordinate for the continuation portion of the graph shown below the main graph is the same as that used above.

Fig. 14 Cirque hydrographs for the 1970-71 season.



NOTE: The ordinate for the continuation portion of the graph shown below the main graph is the same as that used above.

Fig. 15 Cirque hydrographs for the 1970-71 season in terms of discharge/unit area.

seasonal runoff per unit area for the two cirques are also almost identical with values of 15.81 inches on the north and 16.03 inches on the south. The difference between these two is less than 2 per cent. The error associated with these seasonal runoff values cannot be determined directly from the data. In view of the construction of the dams in which the weirs were placed, as well as the weirs themselves, it is believed that the main source of error lies with the reduction of the chart data and not the physical structure. Each time the charts were changed, the stage as indicated by a staff gage located on one end of the dam was read and recorded. No discrepancies between the stage readings and the chart readings were observed. It was, therefore, assumed that the main source of error was with the reduction of the chart data. If it is assumed that the error in each value of the data reduction is one-half the smallest gradation on the chart, i.e., 0.005 feet, and further that the sign of the error was the same on all measurements, an unlikely situation, an error of 1.53 acre-feet of water in the recorded 32.67 acre-feet is obtained on the north cirque while a value of 1.41 acre-feet in the recorded 38.61 acre-feet is obtained on the south cirque. The assumption of the same sign on all readings was made to illustrate that even with this unlikely situation, the error is not sufficient to alter the conclusion. The reason for the larger error on the north cirque resulted from the application of the assumed error to a greater percentage of high head values. Since the discharge is proportionate to the 2.48 power of the head, errors in larger head readings result in much greater errors in discharge than does the same error when applied to a smaller head value.

During the period following the main melt, particularly during late July and August, afternoon showers occurred almost every afternoon. These afternoon showers generally had no noticeable effect on the runoff. For the period following the main melt the major precipitation events as indicated by the recording gage at HAO have been indicated on the hydrographs of Fig. 14. It can be seen that there is generally no effect of these on the flow. When the flow finally ceased on 17 August there was still a sizeable deposit of snow near the ridgeline where the cornice had once been. The volume of water stored in these deposits was estimated as 5.1 acre-feet on the north and 6.9 acre-feet on the south. These deposits, which represent approximately 15 per cent of the measured runoff, were completely melted by mid-October, yet produced no runoff and must be considered with the losses. The water from these deposits was either returned to the atmosphere as evapo-sublimation from the deposit itself or used within the cirque to meet groundwater deficits and evapotranspiration losses. It was observed that the upper portion of the cirque remained moist and covered with lush vegetation long after the lower regions had dried out and the vegetation shown signs of water stress. The water responsible for this difference in vegetal condition could only have come from the slow melt of the remaining cornice formation.

Water-budget for the Feeder Area

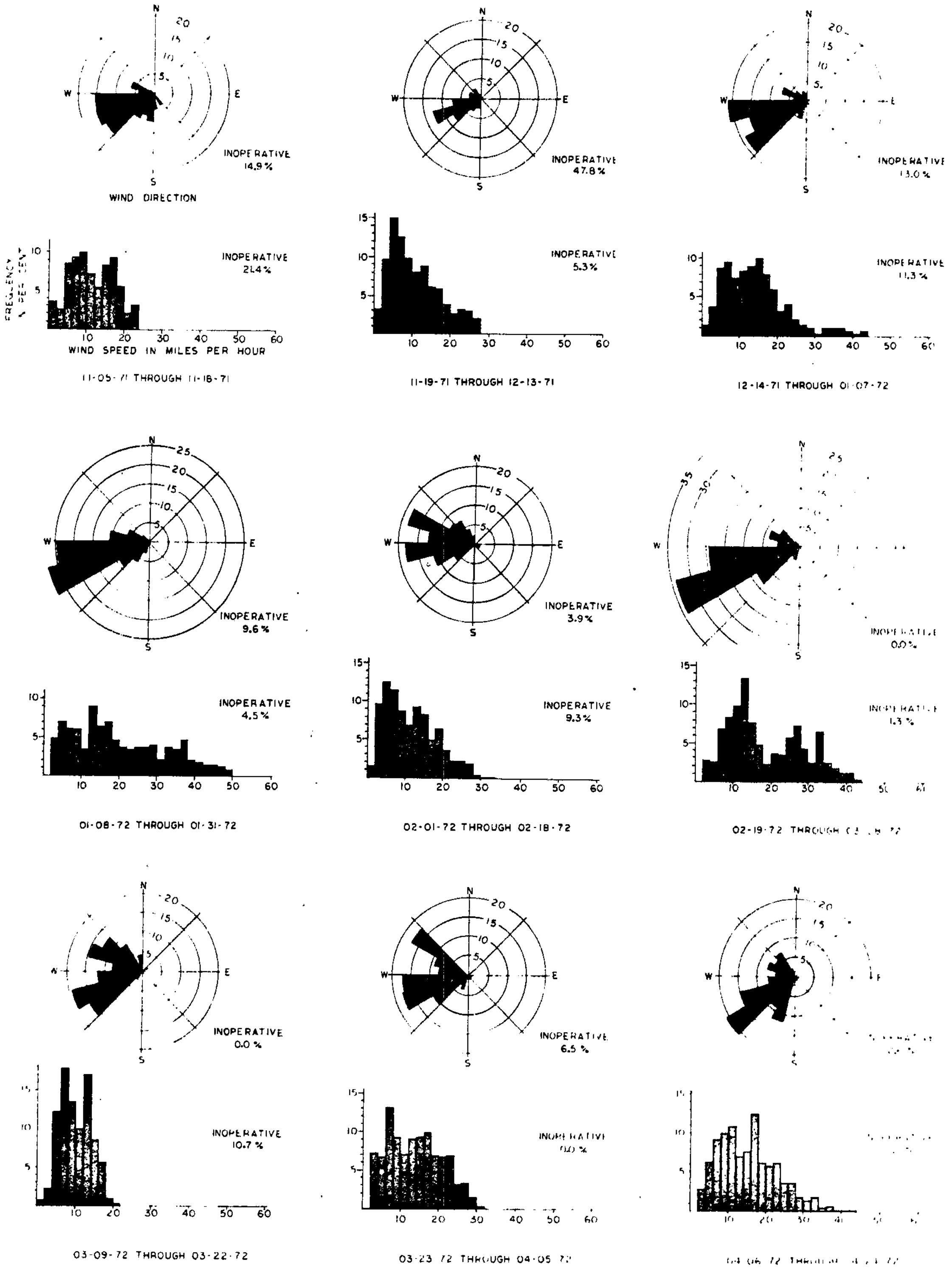
The data necessary to perform the water-budget for each of the time periods included the precipitation during the period, and the snow pack water equivalent at the beginning and end of the period.

The remaining term in the water budget, the combined transport and losses from the area, was found as the residual of the measured quantities.

When these data are considered, it can be seen that the wind speed and direction are among the major controlling factors affecting the reliability of the data collection system. In Fig. 16 the frequency distributions for both the average hourly wind speed and wind direction for each of the sub-periods during the 1971-72 season are shown. The values listed on each of the graphs under "inoperative" is the percentage of time during which each of the recorders was not functioning. This malfunction of the instruments was due primarily to freezing of the ink in the recorders. During the last period, one of the wires broke which connected the anemomitor head located in the feeder area with the recorder housed in the shelter on the north cirque. This condition resulted in a complete loss of wind speed data for this last time period. The wind speed data presented for this last period were obtained from a regression analysis with the data obtained on top of Chalk Mountain which is located 3.7 miles to the southeast (Fig. 1). In this analysis a regression equation based on the data from 1 February through 8 April was used. The equation used was:

$$Y = 3.0 + 0.833\ X$$

in which "Y" is the average hourly wind speed in the study area and "X" is the average hourly wind speed at Chalk Mountain. The linear correlation coefficient for this data was 0.91. The wind direction data for the last period as well as subsequent periods was not



NOTE: The axes on all graphs are as indicated on the one in the upper left position.

Fig. 16 Frequency distributions of the wind speed and direction in the feeder area for the various sub-periods, 1971-72 season.

affected by the malfunction and the data presented are as recorded in the feeder area.

Early in the project it was observed that the precipitation as indicated by several of the gages was much less than that indicated by the other gages. This difference is believed to be due primarily to the exposure of these three gages which were located near the ridgeline and exposed to the full influence of the wind. The mean precipitation as calculated from the entire set of data was thus biased toward the low side. It was also observed that the precipitation as indicated by the readings obtained from the other gages which were located in more sheltered areas were generally less than the change in the water equivalent of the snow pack adjacent to the gage. A representative sample of these data is presented in Table 2. In view of these findings, it was believed that a better estimate of the precipitation in the feeder area could be obtained from snow survey data collected in the forested area just below timberline. Each time that the regular snow surveys were performed in the feeder area, additional data was collected in the timber north of gages Number 3 and 6 and west of gage Number 4. The general location of these snow courses used to estimate the precipitation in the feeder area can be seen in Fig. 3. Although these snow courses were not in the feeder area they are believed to be more representative of the actual precipitation on the area than are any of the values indicated by the gage readings.

In Table 3, the actual gage readings for the various time periods are shown along with the precipitation estimate obtained from the

TABLE 2

Representative Sample of the Gage Readings and Change in Snowpack Water Equivalent Adjacent to the Gage

(All Values are in Equivalent Inches of Water)

Date	11-18 to 12-13		12-13 to 1-08		1-08 to 1-31		1-31 to 2-18	
	Gage	Snow Survey	Gage	Snow Survey	Gage	Snow Survey	Gage	Snow Survey
Gage No.								
1	1.01	2.00	1.11	1.00	1.00	-3.00	0.75	0.00
2	1.13	1.00	0.91	0.50	1.00	-2.00	0.88	0.00
3	0.98	2.00	0.66	4.00	0.68	-1.00	0.32	4.00
4	2.23	4.00	1.64	2.50	1.50	-0.50	1.13	4.00
5	0.88	3.00	0.67	-1.00	0.38	-2.00	0.75	0.00
6	1.93	3.50	1.60	3.50	1.25	3.00	1.00	5.00
7	2.06	0.25	1.08	3.50	0.56	4.00	1.07	6.00
8	1.99	1.50	1.18	1.50	0.69	1.50	1.16	4.50

TABLE 3

Precipitation Data for the Feeder Area

(All Values Listed are Equivalent Inches of Water)

For Period Ending	11-18	12-13	1-08	1-31	2-18	3-08	3-22	4-05	4-24	Seasonal Total
Gage No.										
1	0.65	1.01	1.11	1.00	0.75	0.13	0.00	0.50	-.50	5.15*
2	0.22	1.33	0.91	1.00	0.88	0.13	0.13	0.37	-.56	4.96*
3	1.57	0.98	0.66	0.68	0.32	0.44	0.12	0.43	-.06	5.20*
4	1.33	2.23	1.64	1.50	1.13	0.96	0.00	0.88	-.18	9.67*
5	0.00	0.88	0.67	0.38	0.75	0.06	0.00	0.20	-.25	2.94*
6	0.66	1.93	1.60	1.25	1.00	1.06	0.07	1.00	-.63	8.57*
7	0.66	2.06	1.08	0.56	1.07	0.13	0.00	0.63	-.30	6.19*
8	0.67	1.92	1.18	0.69	1.16	0.75	0.25	0.37	-.38	6.99*
Mean	0.72	1.54	1.11	0.88	0.88	0.45	0.07	0.55	0.00	6.20
Standard Error of the Mean (±)	0.15	0.20	0.13	0.13	0.10	0.15	0.03	0.10	N.A.	
Max. Recorded	1.57	2.23	1.64	1.50	1.16	1.06	0.25	1.00	0.00	10.41
Snow Survey Estimate	2.25	4.00	4.00	4.00	3.75	2.75	1.00	4.25	2.50	28.50
Standard Error of the Mean (±)	0.10	0.05	0.06	0.06	0.03	0.04	0.03	0.10	0.08	
FOR COMPARISON PURPOSES										
HAO	0.24	2.25	1.44	1.19	1.95	1.46	0.53	0.75	1.83	11.64
Cirques (Mean Value)		2.12	2.33	2.03	0.98	1.87	1.16		1.82	12.31

*Does not include negative value indicated during last period.

snow surveys performed in the timber area. Various statistics as well as the gage readings from the cirques and HAO have also been included for comparison purposes.

The wind also had a pronounced effect on the distribution of the snowcover in the feeder area. This effect was not believed to be truely represented by the mean of the snow survey measurements taken at the 39 sampling stations. Thus isohyetal maps of the water equivalent of the snowpack were constructed for each of the time periods. These maps were based on the snow survey data as well as field sketches of the line of zero snow cover, drift patterns in the area, and the wind data for the period. These maps, along with the average water equivalent based on the map data, are shown in Fig. 17. The dashed line shown on most of the maps and labeled "0" is not truely a line of zero snow cover, but rather a line beyond which the water equivalen of the snow was so small that it could not be accurately estimated as any measurable quantity. The water stored in these regions was in the form of very small drifts on the lee side of small rocks and the sparse clumps of grass common to the area. The error associated with the average water equivalent obtained from the maps cannot be directly determined from the data. The standard error of the mean of the 39 snow sample data used in preparing each of the maps is not representative of the error associated with the average water equivalent over the area. A simple glance at any of the maps reveals that none of the stations can be considered as an estimate of the mean value; the data cannot be considered as measures of the same quantity; and the data are not normally distributed. When these conditions are imposed, it can be seen that the probable

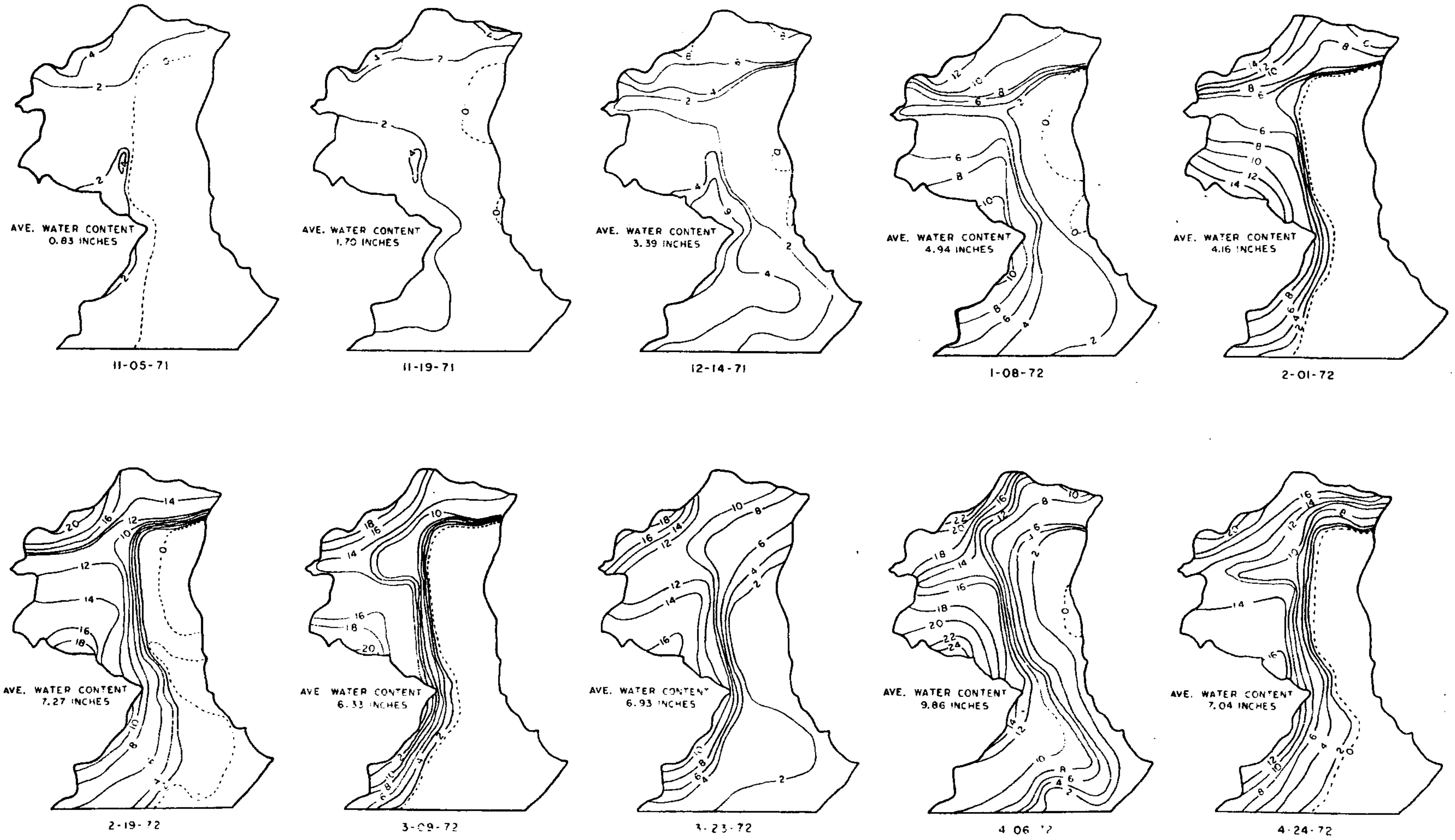


Fig. 17 Isohyetal maps of the snow cover water equivalent in the feeder area on the dates indicated.

error associated with the average value for the water equivalent of the snowpack in the feeder area is, at best, a guess. However, in order to remain unbiased, the standard error of the mean will be used as an estimate of the error. It is realized that this value is probably much larger than the actual error associated with the average value. However, if the conclusions presented can be substantiated with this estimate of the error, then they must also be substantiated with any other estimate which is smaller in magnitude.

The transport from the feeder area, obtained by combining the change in water equivalent of the snowpack with the estimates of the precipitation for each of the periods, is shown in Table 4. For comparison purposes the computations have been presented for both the mean of the 39 snow survey samples and the average values as obtained from the isohyetal maps. Values of the transport utilizing the three estimates of precipitation previously discussed, i.e., the mean, the maximum recorded, and the snow survey estimate, have also been included for comparison purposes. The estimate of the transport based on the average water equivalent obtained from the maps and the snow survey estimate of the precipitation is believed to be the best estimate of the actual transport that can be obtained from this data set. As mentioned previously the error associated with the average water equivalent obtained from the maps will be assumed to be the same as the standard error of the mean of the 39 snow survey measurements. The error associated with the transport value was obtained by taking the square root of the sum of the squares of the error associated with each of the terms in the water-budget equation. In Table 4, it can be seen that it is the standard error of the mean of the 39 snow

TABLE 4

Transport From the Feeder Area

(All Values are in Equivalent Inches of Water)

For Period Ending	11-18	12-13	1-07	1-31	2-18	3-08	3-22	4-05	4-24	Seasonal Values
Snowpack Water Eq. at Beginning of Period										
Mean	1.43	1.86	4.15	6.08	4.95	8.62	7.14	7.10	10.02	1.43
Standard Error of the Mean (±)	0.27	0.24	0.37	0.51	0.72	1.03	1.11	0.91	1.15	0.27
Map Ave.*	0.83	1.70	3.39	4.94	4.16	7.27	6.33	6.93	9.86	0.83
Snowpack Water Eq. at End of Period										
Mean	1.86	4.15	6.08	4.95	8.62	7.14	7.10	10.02	7.75	7.75
Standard Error of the Mean (±)	0.24	0.37	0.51	0.72	1.03	1.11	0.91	1.15	1.06	1.06
Map Ave.*	1.70	3.39	4.94	4.16	7.27	6.33	6.93	9.86	7.04	7.04
Change in Storage Based on:										
Mean (1)	-0.43	-2.29	-1.93	1.13	-3.67	1.48	0.04	-2.92	2.27	-6.32
Prob. Error (±)	0.36	0.44	0.63	0.88	1.26	1.51	1.43	1.46	1.56	1.09
Map Ave.* (2)	-0.87	-1.69	-1.55	0.78	-3.11	0.94	-0.60	-2.93	2.82	-6.21
Prec. During Period										
Mean (3)	0.72	1.54	1.11	0.88	0.88	0.45	0.07	0.55	0.00	6.20
Max Recorded (4)	1.57	2.23	1.64	1.50	1.16	1.06	0.25	1.00	--	10.41
Snow Survey Estimate (5)	2.25	4.00	4.00	4.00	3.75	2.75	1.00	4.25	2.50	28.50
Transport Based on:										
1 & 3	0.29	-0.75	-0.82	2.01	-2.79	1.93	0.11	-2.37	2.27	-0.12
Prob. Error (±)	0.39	0.48	0.64	0.89	1.26	1.52	1.43	1.47	1.56	1.16
1 & 4	1.14	-0.06	-0.29	2.63	-2.51	2.54	0.29	-1.92	2.27	4.09
1 & 5	1.82	1.71	2.07	5.13	0.08	4.25	1.04	1.33	4.77	22.18
Prob. Error (±)	0.37	0.44	0.63	0.88	1.26	1.51	1.43	1.47	1.56	1.11
2 & 3	-0.15	-1.15	-0.44	1.66	-2.23	1.39	-0.53	-2.38	2.82	-0.01
2 & 4	0.70	0.60	0.09	2.28	-1.95	2.00	-0.35	1.93	2.82	4.20
2 & 5	1.38	2.31	2.45	4.78	0.64	3.69	0.40	1.32	5.32	22.29
Prob. Error (±)	0.37	0.44	0.63	0.88	1.26	1.51	1.43	1.47	1.56	1.11

*Error assumed to be same as standard error of the mean of the 39 snow sample data.

survey data which controls the magnitude of the error associated with the transport value. The error in the precipitation values has only minor effects on the estimated error associated with the transport. The transport values listed as negative quantities imply that in order for the water-budget to be balanced, a net transport of water into the area must have occurred. When the field situation is considered, the net transport into the area suggested by some of the values is highly unlikely.

Components of the Transported Snow

The transported water from the feeder area was defined as containing both the evapo-sublimation losses from the main snow cover and the snow physically moved out of the area by the wind. The portion carried by the wind may be further divided into the portion caught in the cornice-windslab deposit, the fallout, the portion carried by the general overall circulation into the valley, and the evapo-sublimation loss occurring during the transport process.

Utilizing Procedure No. 1 as discussed in Appendix A, the portion of the total transport from the entire potential feeder area which passed over each of the cirques was calculated. If the assumptions presented in the development of this procedure are accepted, then the sources of error, other than those associated with the computation of the total transport, originate with the wind data and the size of the effective feeder area associated with each division of the wind direction groupings. The validity of the assumptions cannot be tested from this data set, or any other, until such time that reliable equipment is made available for the continuous monitoring of the actual transport over the ridgeline on each cirque. Since such instrumentation was not available, the error associated with the transport over each of the cirques must be considered as an "educated guess." In view of the discussion presented in Appendix A, the assumptions were accepted as being reasonable and thus the estimated error was computed on the statistics associated with the wind data. The procedure used consisted of randomly selecting 20 hourly periods for which the standard deviations in the wind direction was computed. The standard deviations were then averaged and the average value (+ and -) applied to the average hourly wind directions, the effective area computed, and the percentage of the total transport which passed over each cirque recalculated. The maximum difference between the average value and the adjusted value was assumed as the estimate of the error for the particular period under investigation. These values are included, with others, in Table 5. Here it can be seen that the error in the total transport resulting from the use of the standard error of the mean of the snow survey data is so large that the effect of the other errors is unnoticed. However, even with the use of this large value for the possible error in the snow pack water equivalents, the estimated error in the seasonal values is less than 5 per cent.

The volume of the snow stored in the cornice deposit on each of the cirques was determined through two different procedures, field surveys and photogrammetric techniques. With the stereo photographs the orientation of the camera for each photo was determined by using three control points shown in each photograph and conventional reduction techniques.[10] Knowing the orientation of each photograph, the spacial co-ordinates of both the top and bottom of the leading face of the cornice deposit was determined by using direction cosignes at approximately 25 foot intervals along the entire length of the deposit. These values were then superimposed upon the ground profiles as determined from the topographic maps prepared of the area. From this combination of data, the area of the various cross-sections, and thus the volume of the deposit, was computed. The same basic procedure was used with the field survey data except that the spacial co-ordinates of the leading edge of the formation was determined by using a 16 foot pole graduated every 6 inches and a hand level for determining the elevation of the leading edge of the ridgeline deposit. The same spacing, i.e., approximately 25 feet, along the length of the deposit was used. By combining the volume measurement with the data for the density of the formation obtained from core samples, the volume of water stored in the deposit was calculated. These values are shown in Tables 6A and 6B.

The error associated with these measurements is again impossible to determine directly from the data. However, on several pairs of photographs, there were four control points visible. By using any three of the points, the computed co-ordinated of the fourth could be obtained and compared to the known values. When this was done, the maximum difference encountered was 0.7 feet with an average value for 12 such comparisons of 0.44 feet. If it is assumed that the error associated with a measurement of the snow surface is the same as for

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[10] For details see Moffitt (1959), pg. 199-225.

TABLE 5

Transport Over Each Cirque

For Period Ending	11-18	12-13	1-07	1-31	2-18	3-08	3-22	4-05	4-24	Season
Total Transport from the Feeder Area										
in inches	1.38	2.31	2.45	4.78	0.64	3.69	0.40	1.52	5.32	22.29
in ac.-ft.	46.30	77.50	82.19	160.36	21.47	123.79	13.42	50.78	178.12	753.93
Possible Error in ac.-ft. (±)	12.4	14.7	21.4	28.0	42.4	50.6	47.8	56.4	52.3	37.3
Possible Error in % (±)	26.8	19.0	25.7	17.4	197.0	41.0	357.5	111.2	29.4	4.95
Effective Feeder Area in Per Cent										
North Cirque	12.3	13.9	14.3	15.6	15.0	15.4	13.2	14.8	11.8	14.06
Possible Error in % (±)	0.1	0.2	0.1	0.1	0.2	0.1	0.3	0.1	0.1	0.12
South Cirque	16.2	16.7	17.0	16.8	15.9	16.1	15.3	15.2	16.0	16.10
Possible Error in % (±)	0.1	0.2	0.1	0.1	0.2	0.1	0.2	0.1	0.1	0.12
Transport Over Each Cirque										
North Cirque	5.69	10.76	11.71	24.95	3.21	19.08	1.77	7.52	21.00	105.69
Possible Error in % (±)	26.8	19.0	25.7	17.4	197.0	41.0	357.5	111.2	29.4	4.95
Possible Error in ac.-ft. (±)	1.53	2.04	3.00	4.34	6.31	7.81	6.32	8.36	6.18	5.24
South Cirque	7.52	12.97	13.95	26.94	3.42	19.95	2.06	7.73	28.47	123.01
Possible Error in % (±)	26.8	19.0	25.7	17.4	197.0	41.0	357.5	111.2	29.4	4.95
Possible Error in ac.-ft. (±)	2.02	2.46	3.58	4.68	6.74	8.16	7.37	8.59	8.39	6.10

TABLE 6A

Components of the Transport Over the North Cirque

For Period Ending	11-18	12-13	1-07	1-31	2-18	3-08	3-22	4-05	4-24	Season
Total Transport										
in ac.-ft.	5.69	10.76	11.71	24.95	3.21	19.00	1.77	7.52	21.00	105.69
Possible Error in ac.-ft. (±)	1.53	2.04	3.00	4.34	6.31	7.81	6.32	8.36	6.18	5.24
Cornice Storage Including Avalanche Material										
Volume in ac.-ft.	8.70	17.89	23.86	44.55	46.80	52.60	59.31	63.82	68.42	68.42
Possible Error in ac.-ft. (±)	0.06	0.12	0.16	0.30	0.32	0.35	0.40	0.42	0.46	0.46
Density in %	46	53	53	59		58	54		57	
Standard Error of the Mean (±)	1.0	0.5	0.2	0.3		0.1	0.2		0.3	
Vol. of Water in ac.-ft.	4.00	9.47	12.65	26.34	27.37	30.48	32.01	35.42	38.99	38.99
Possible Error in ac.-ft. of Water (±)	0.21	0.21	0.15	0.26	0.28	0.22	0.35	0.60	0.39	0.41
Change in Cornice Storage										
in ac.-ft. of Water	4.00	5.47	3.18	13.69	1.03	3.11	1.53	3.41	3.58	38.99
Possible Error in ac.-ft. of Water (±)	0.21	0.30	0.26	0.26	0.25	0.22	0.11	0.60	0.72	0.41
Fallout										
in ac.-ft. of Water	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Error - see text for discussion										
Transport into Lower Valley										
in ac.-ft. of Water	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Error - see text for discussion										
Losses										
in ac.-ft. of Water	1.69	5.29	8.53	11.26	2.18	15.97	0.24	4.11	17.42	66.70
Possible Error in ac.-ft. of Water (±)	1.54	2.06	3.00	4.34	6.31	7.81	6.32	8.36	6.18	5.24

TABLE 6B

Components of the Transport Over the South Cirque

For Period Ending	11-18	12-13	1-08	1-31	2-18	3-08	3-22	4-05	4-24	Season
Total Transport										
in ac.-ft.	7.52	12.97	13.95	26.94	3.42	19.95	2.06	7.73	28.47	123.01
Possible Error in ac.-ft. (±)	2.02	2.46	3.58	4.68	6.74	8.16	7.37	8.59	8.39	6.10
Cornice Storage										
Volume in ac.-ft.	11.09	22.15	29.31	37.30	38.50	44.00	47.90	48.80	49.76	49.76
Possible Error in ac.-ft. (±)	0.12	0.24	0.30	0.40	0.42	0.48	0.52	0.53	0.54	0.54
Density in %	46	53	53	59		58	54		57	57
Standard Error of the Mean (±)	1.0	0.5	0.2	0.3		0.1	0.2		0.3	0.3
Vol. of Water in ac.-ft.	5.10	11.73	15.50	22.01	22.56	25.54	25.83	27.07	28.38	28.38
Possible Error in ac.-ft. of Water (±)	0.34	0.20	0.28	0.31	0.47	0.29	0.27	0.76	0.30	0.30
Change in Cornice Storage										
in ac.-ft. of Water	5.10	6.63	3.77	6.51	0.55	2.96	0.31	1.24	1.31	28.38
Possible Error in ac.-ft. of Water (±)	0.34	0.39	0.34	0.38	0.56	0.55	0.40	0.81	0.82	0.30
Fallout										
in ac.-ft. of Water	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Error - see text for discussion										
Transport into Lower Valley										
in ac.-ft. of Water	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Error - see test for discussion										
Losses										
in ac.-ft. of Water	2.42	6.34	10.18	20.43	2.87	16.99	1.75	6.49	27.16	94.63
Possible Error in ac.-ft. of Water (±)	2.03	2.48	3.58	4.68	6.74	8.16	7.37	8.59	8.39	6.10

the control points, an error of approximately 0.5 feet is obtained. If it is further assumed that this same error can be expected for the field survey data, an estimate of the error associated with each of the cross-sections can be obtained. If it is assumed that the sign of the error is the same on each cross-section, an unlikely situation, an estimate of the volume error is obtained. This last assumption, i.e., that the errors are all of the same sign, was specifically made to illustrate that even though the magnitude of the possible error associated with the spacial co-ordinates of the measured points is large, 6 inches, the relative error associated with the overall volume of the deposit is quite small.

The error associated with the volume measurements of the deposit are not the only errors associated with the water equivalent. Since the water equivalent was determined by multiplying the volume by the density, errors in the density measurements could also effect the estimate of the water equivalent of the cornice deposit. Throughout the winter, core samples were taken of the cornice deposits and the density computed. These values ranged from 52 to 64 per cent. The value of 54 per cent was obtained in a small area of new cornice formed during the extreme wind conditions encountered during January 1972 and was somewhat higher than the normal values encountered. The values of the mean density of the deposit for each of the days when measurements were taken were observed to vary from period to period depending on the anticedent wind conditions. The values taken on any one day were, however, seen to be very uniform. The mean of the density measurements along with the standard error of the mean for the various days when measurements were taken are shown in Tables 6A and 6B.

For those periods when density measurements were not taken, the density of the deposit was assumed to be the average of measurements for the adjacent time periods. The combined error associated with the water equivalent of the cornice deposit was found as the square root of the sum of the square of the error associated with the volume measurement and the standard error of the mean of the density measurements. It should be remembered that this value is somewhat of an "educated guess" in that an estimate of the error associated with the volume measurement of the cornice cannot be obtained directly from the data.

The fallout into the cirques was determined from replicator profiles performed in the cirques on four different occasions during the winter period. The results of all of the replicator data as well as numerous visual observations indicated that there was no fallout into the cirques. These data, however, were limited to periods when no precipitation was occurring in the region yet visible transport of blowing snow was observed at the ridgeline. This observation of no fallout into the cirques can be interpreted as meaning one of two things; either the particles sublimate as they travel through the air space between the ridgeline and the cirque floor, or the primary circulation within the cirque during transport periods is sifficient to keep the particles suspended in the airflow. If the first argument is used, then for those periods when the relative humidity within the cirques is above approximately 87 per cent, no sublimation should occur and fallout should result. From the cumulative frequency distribution of relative humidities for the cirques, which is shown in Fig. 18, it can be seen that this condition occurred 33 per cent of the time. Since the maximum relative humidity recorded during any of

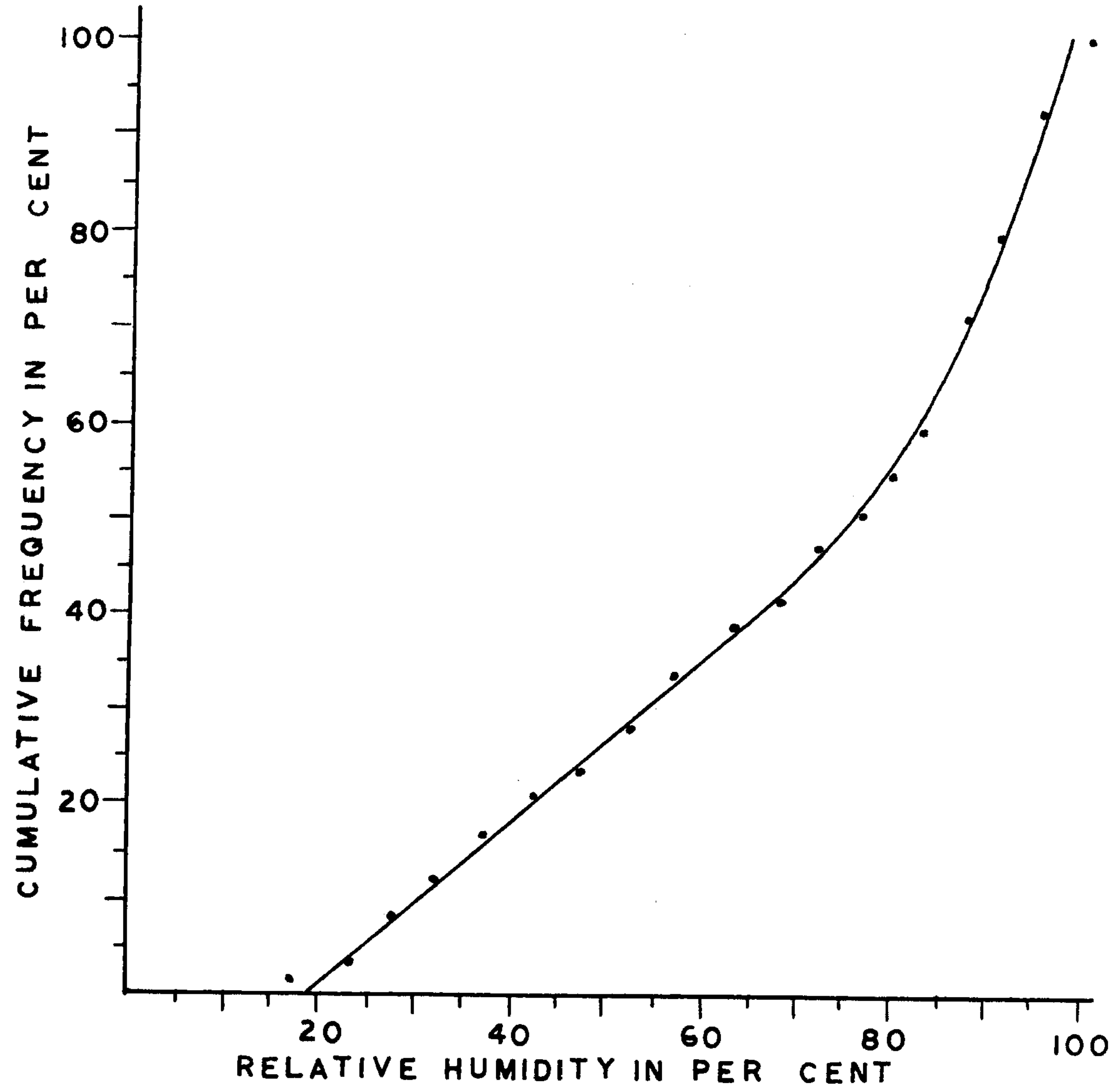


Fig. 18 Cumulative frequency distribution of the relative humidity in the cirques during the 1971-72 season.

the replicator profiles was 81 per cent, it can be concluded that fallout did not occur at least 55 per cent of the time. The occurrence of fallout during the remaining 12 per cent of the time, i.e., for relative humidities between 81 and 87 per cent, is uncertain. However, if fallout did occur during the periods of high relative humidity and thus during the precipitation periods as well, it is reasonable to assume that the combined accumulation of precipitation plus fallout would be at least equal to the precipitation as recorded near timberline on the western edge of the feeder area. When the snow survey estimates of the precipitation in the feeder area are compared to the gage reading of precipitation in the cirques (Table 2), or the snow survey data for the water equivalent of the snow pack in the cirques at the end of the winter period (Fig. 20), it can be seen that there is less water in the cirques than in the timber west of the feeder area. Thus the combination of precipitation plus fallout into the cirques is less than the precipitation in the feeder area. The argument concerning fallout during periods of high relative humidities cannot be substantiated by the data. The second argument, i.e., the particles are held in suspension by the airflow, is also questioned. If the particles were merely held in suspension, then they should reflect the incident sunlight and be visually apparent, at least on a clear day. Such conditions were not observed. It is therefore proposed that the major portion of the transport particles leaving the ridge are carried by the main airflow and only a very small portion enter the primary circulation on the leeward side of the ridge. Those particles which due enter this circulation during periods when the relative humidity is below approximately 80 per cent sublimate before they reach the cirque floor. Furthermore, during transport periods, the primary circulation on the leeward side of the ridge tends to retard the downward motion of the particles into the cirques thus accounting for at least a portion of the indicated reduction in water entering the cirques.

In view of the arguments presented, it will be assumed that there was no fallout into the cirques. If there actually was some fallout which enters the cirques during the periods of high relative humidities, this assumption will cause an error in the water-budget analysis for the feeder area. This water however, would be recorded in the precipitation measurements and snow surveys measurement within the cirques and thus be accounted for in the water-budget analysis for the cirques. Since the evaluation of the management effort was based on the water-budget analysis for the cirques, any error in the measurement of the fallout will not affect this evaluation.

The portion of the total transport which was carried by the circulation into the lower valley is another term which will only influence the water-budget analysis for the feeder area. Since this term does not enter into the analysis for the cirques, it cannot influence the evaluation of the management effort. In hopes of obtaining an estimate of the possible magnitude of this transport into the lower valley, a snow survey was performed on 29 April when the maximum accumulation of the winter precipitation was anticipated. The route of the survey and the average water equivalent of the snowpack at each of the sampling stations are shown in Fig. 19. Due to the terrain immediately east of the cirques, it was necessary to first move in a southerly direction from the cirques before heading in an

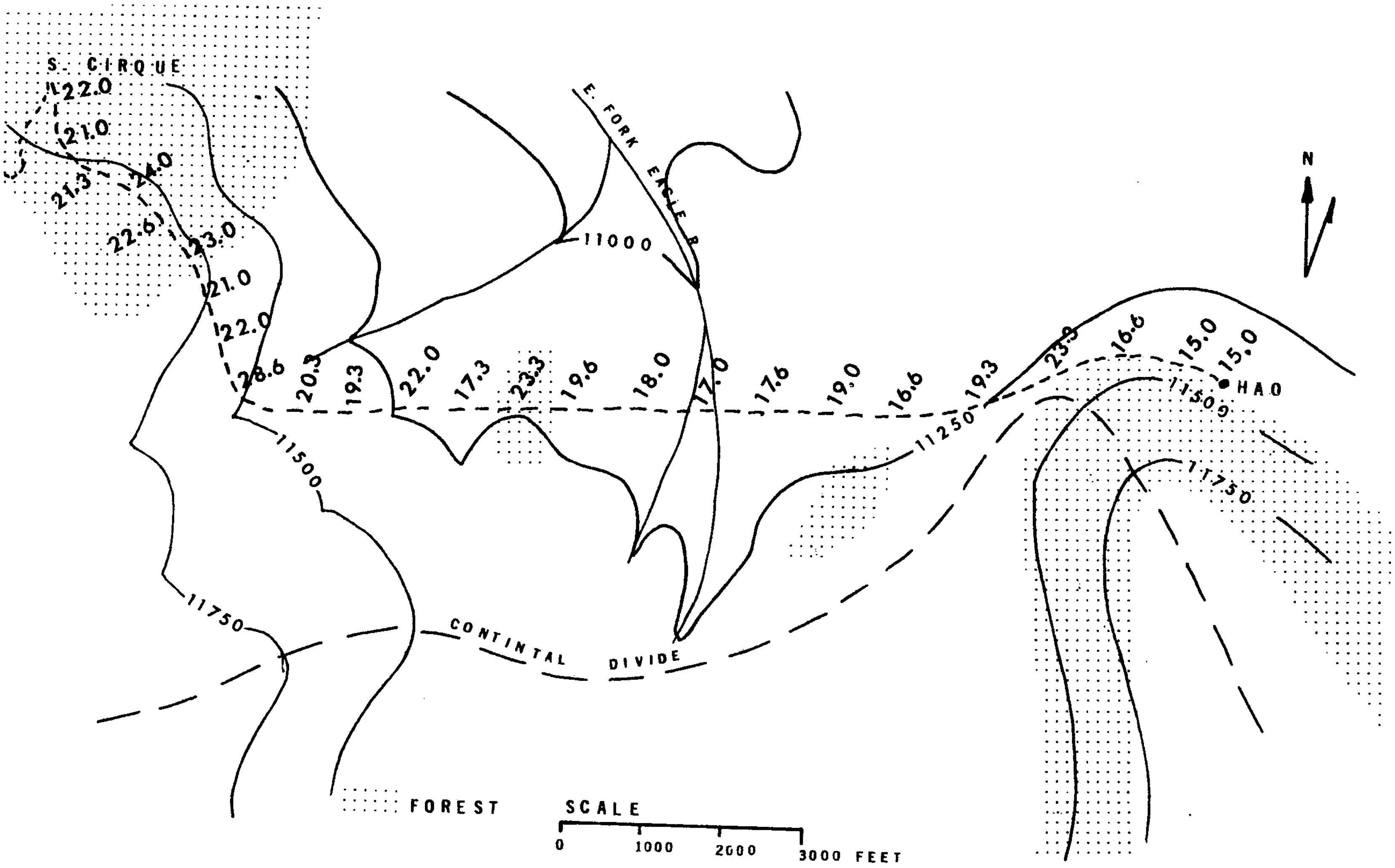


Fig. 19 Snow survey data for estimating the valley transport.

easterly direction toward HAO. At each sampling site, 3 samples were taken. The maximum difference between the readings at any one site was 1 inch of water equivalent. From these data it can be seen that no region of increased water equivalent of the snowpack could be found. In view of these findings, and the subsequent discission, it was assumed that there was no transport into the lower valley and that the error associated with this estimate was zero. Here again the validity of these assumptions cannot be directly tested from the data set. However, if there was any sizeable transport into the lower valley, the combination of transport plus precipitation should be larger than the indicated precipitation in the feeder area which is not the indicated condition.

Further insight into the validity of the assumptions of no fallout and no valley transport can be obtained by considering the theoretical model on sublimation of wind-transported snow developed by Schmidt (1972). Considering Schmidt's model, an ice sphere 100 μ in diameter under a ventilation of 100 cm/sec. will loose approximately 19 per cent of its mass in the first 1 minute of travel in an environment with 90 per cent relative humidity over ice at 100 mb. pressure, -20°C, and no radiation transfer. If the environmental conditions are adjusted to include radiation effects, a 750 mb. pressure (approximately 12,000 ft) and a temperature of -10°C the calculated loss in the first minute of travel is increased to 45.6 per cent of the mass of the particle. Let it further be assumed that a particle is traveling along the separation between the primary circulation and the ambient flow, and the average trajectory of the particle is one vertical to four horizontal. If the particle moves with the wind at an average speed of 30 mph and decends 1000 feet to the valley floor, it will take almost four minutes for the travel. However, according to Schmidt, 45.6 per cent of the mass of the particle will have sublimated during the first minute of travel in the environment previously described. Since the percentage loss increases with a decrease in diameter, it can be seen that such a particle cannot travel from the top of Chicago Ridge into the valley under the conditions sited. Since the environmental conditions sighted are representative of the conditions encountered in the study area, and further since the field conditions should result in greater sublimation than the steady state conditions assumed by Schmidt, it is reasonable to assume no valley transport. When the upslope conditions in the cirque are considered, it can be seen that the assumption of no fallout is also supported by the theoretical model.

The losses from the feeder area were determined by performing the water-budget analysis as indicated in the previous discussion. From the values listed in Tables 6A and 6B it can be seen that for the various sub-periods the error associated with the data is such that no reliable estimate of the transport can be made. This apparent condition results from the use of the standard error of the mean of the 39 snow survey data as the estimate of the error associated with the average water equivalent of the snow pack in the feeder area. As was previously noted the actual error cannot be determined from the data and the choice of this value, knowing it to be in error, was made to prevent undue bias in the conclusions. However, when the water-budget is performed on the seasonal values it can be seen in Tables 6A and 6B that the influence of the choice of the standard error of the mean of the 39 snow survey data is much less. When the seasonal values are used for the north cirque it can be seen that 63.5 (±1.5) per cent of the precipitation on the feeder area cannot be accounted for as stored water in the snowpack anywhere in the general vicinity of the study area. The values for the south cirque which did not receive any treatment effect indicate that the losses from the natural system are 77.0 (±6.0) per cent. This water which was lost from the system is believed to have sublimated from both the natural snowpack in the alpine as well as from the migratory snow during the transport process. The full significance of this loss will be discussed in detail in later sections.

Water-budget for the Cirques

In the previous discussion, it was stated that the water-budget for the cirques contained as input into the system, the winter precipitation, the fallout, the valley transport, the cornice storage, and the precipitation occurring during the melt period. If the winter precipitation, the fallout and the valley transport are grouped together and estimated from snow survey data of the actual snow pack in the cirques at the time when the maximum winter accumulation was anticipated, then the error in the snow survey data includes any possible errors which may have been made in the measurements of the individual quantities. Here, as in the feeder area, the snow survey data were combined with data on the local drift patterns and topography and an isohyetal map of the snowpack water equivalent compiled. This map is shown in Fig. 20. In developing this map, 12 separate transects covering various parts of the drainage area were performed with sampling stations at an interval of 5 paces, approximately 15 feet, and

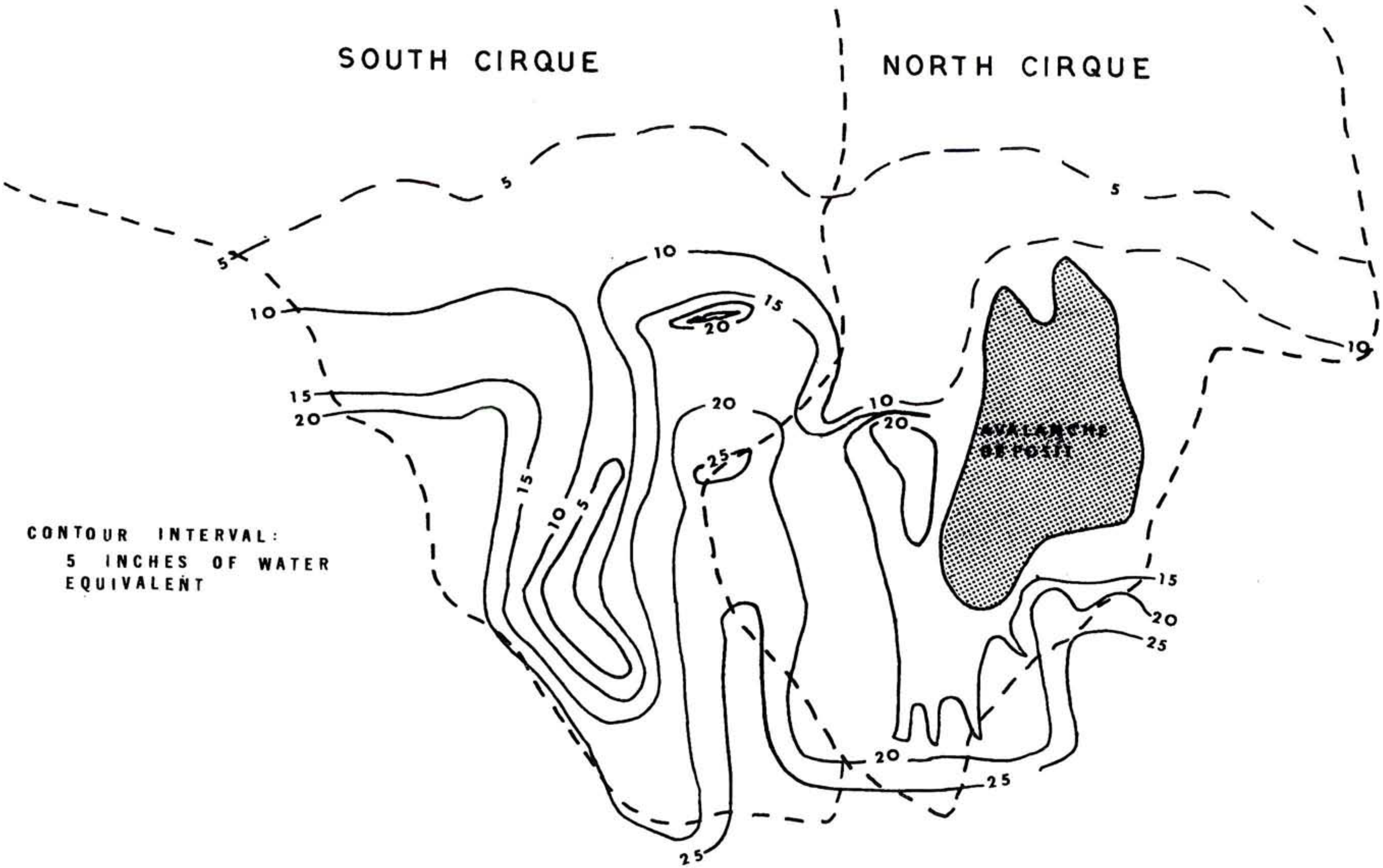


Fig. 20 Isohyetal map of the snow pack water equivalent in the cirques, 29 April 1972.

the transects at a spacing of 10 paces, approximately 30 feet. Two regions of the cirques were not included in the surveyed area. One, the slide area for natural avalanches, was excluded for safety reasons, while the other, the deposit resulting from the management effort, was impossible to penetrate with the conventional snow survey equipment. Estimates of the storage in the natural slide area were determined from snow depth markers located in the slide area and assuming the same density was the same as measured at the upper limit of the survey region. For the area covered by the management deposit, it was assumed that the water equivalent of the natural snow pack in this region was the same as for the surrounding areas. The average water equivalent of the snow pack in each of the cirques computed from the maps was 12.78± inches on the north and 13.45± inches on the south. In terms of acre-feet, these values represent 26.52± and 32.39± respectively.

The error associated with these values, again, cannot be directly evaluated from the data. An estimate of the error can be obtained from the standard error of the mean of the 273 snow sample data. However, the limitations in using this value, as noted for the feeder area, also apply to its use with the cirque data. The error estimate so obtained is probably much greater than the actual error associated with the average water equivalent of the snowpack. However, it does eliminate any bias induced into the conclusions by merely assuming, or guessing, at a reasonable value. All values used in the water-budget analysis are shown in Table 7.

The other two terms which contribute to the inflow in the water-budget analysis are the precipitation after the time of the snow survey measurements and the water stored in the cornice-windslab deposit on each cirque. Each of these values have been previously discussed and are shown with the associated errors separately in Tables 1 and 6A and 6B respectively, as well as in Table 7 which summarizes the water-budget analyses for the cirques.

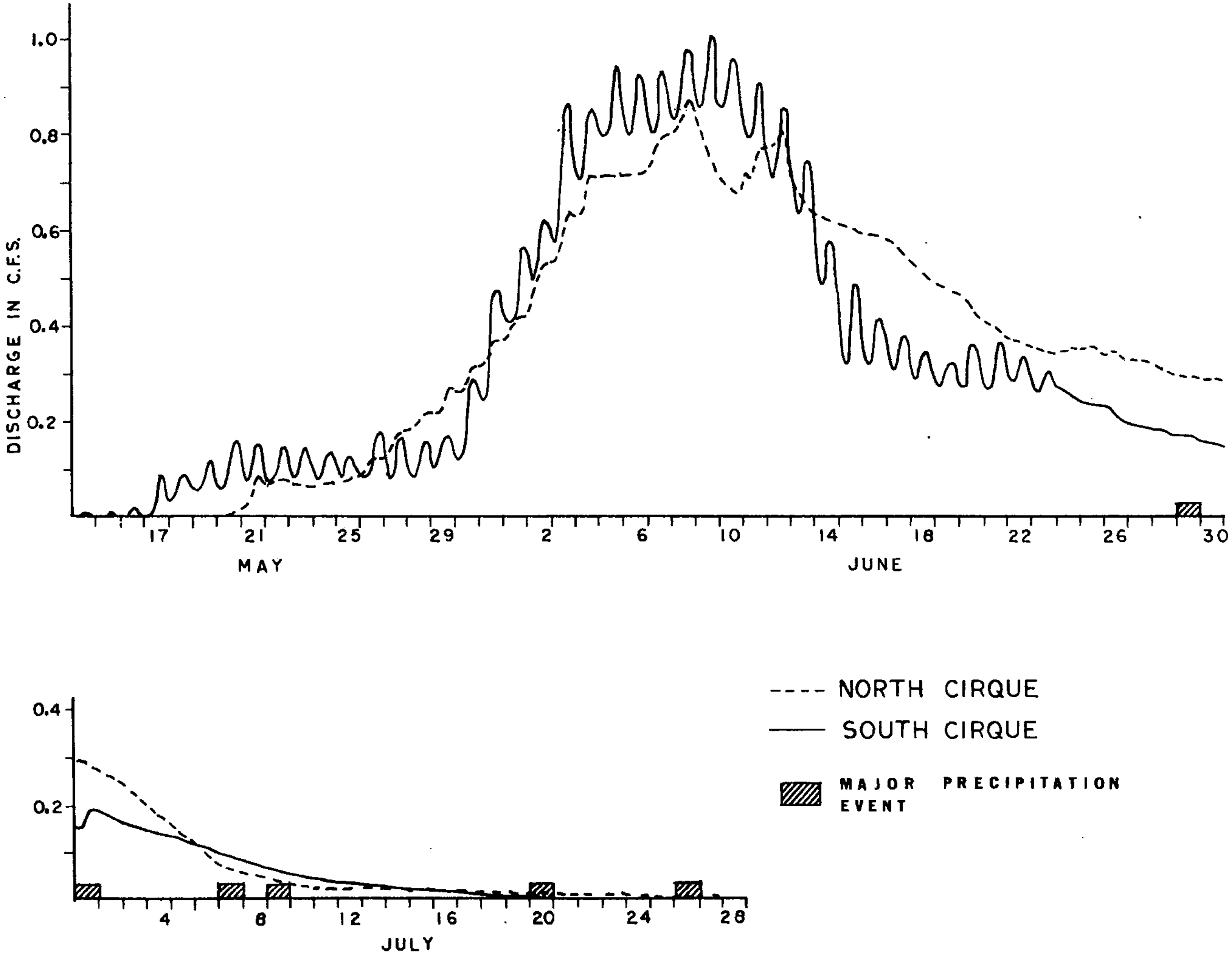
The hydrographs of actual runoff and runoff per unit area for each of the cirques are shown in Figs. 21 and 22 respectively. When these two graphs are compared to the graphs of Figs. 14 and 15, which are for the previous season, it is readily apparent that the large fluctuations in daily flow noted on the south cirque during the 1970-71 season are not as pronounced during the 1971-72 runoff period. The main reason for this difference is believed to be that during the 1970-71 season the night temperatures during the main melt period almost always dropped to or below the freezing point, while during the latter season this condition rarely occurred. This slight refreezing of the pack during the late evening and early morning hours not only retards the overall melt rate, thus lengthening the period of major runoff, but also alters the time of the daily maximum and minimum flows. Without the nightly refreezing, the melt of the pack is much less uniform over the area than was noted during the previous season. When the nightly freezing occurred was most predominate in the open area which also experienced the maximum rate of heating during the daylight hours. Since the open areas froze to a greater extent during the night, they required a greater amount of heat during the day to bring about the same amount of melting. The resulting effect was the complete melt of the snowpack over the entire area at approximately the same time. This condition is indicated by the sudden decrease in

TABLE 7

Water-budget for the Cirques

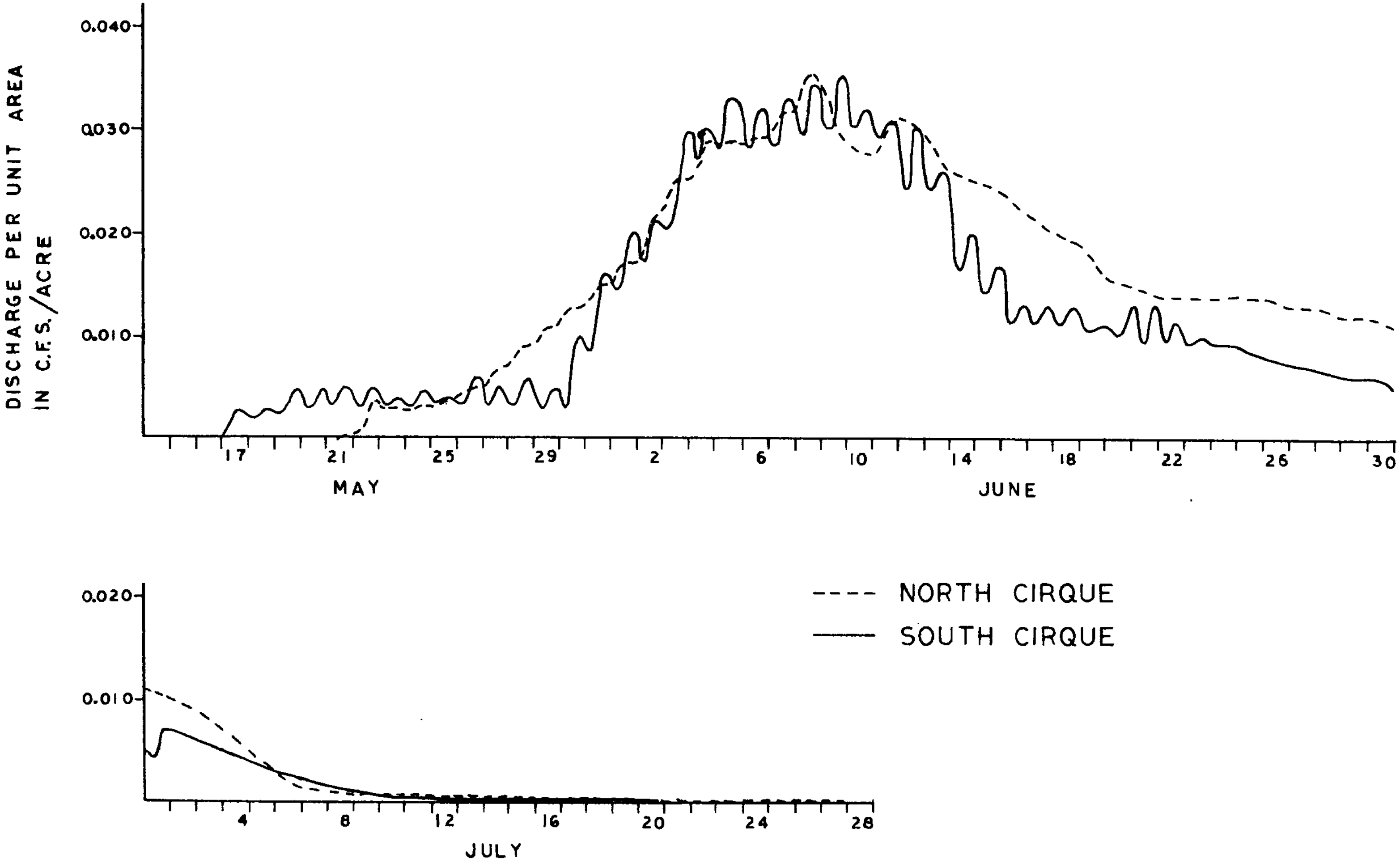
	South		North	
Snowpack water equivalent in ac.-ft.	32.4	±2.61	26.5	±2.18
Cornice storage in ac.-ft.	28.4	±0.30	39.0*	±0.41
Precipitation during melt period in ac.-ft.	6.1	±0.07	5.2	±0.06
Total water available for funoff in ac.-ft.	66.9	±2.63	70.2	±2.22
Observed runoff in ac.-ft.	35.9	±1.46	39.3	±1.61
in inches	14.9	±0.60	19.0	±0.78
Runoff coefficient	.537	± .003	.555	± .003
Losses in ac.-ft.	31.0	±3.00	31.4	±2.55
in inches/acre of cirque	12.9	±1.2	15.2	±1.2
in per cent	46.4	±3.7	44.4	±3.2

*Includes avalanche material.



NOTE: The ordinate for the continuation portion of the graph shown below the main graph is the same as that shown above.

Fig. 21 Cirque hydrographs for the 1971-72 season.



NOTE: The ordinate for the continuation portion of the graph shown below the main graph is the same as that used above.

Fig. 22 Cirque hydrographs for the 1971-72 season in terms of discharge/unit area.

flowrate particularly evident on the south cirque hydrograph of Fig. 14. Without this condition of daily freezing and thawing, the melt in the open areas was complete several days before it was in the wooded areas. Thus, the sudden decrease in flowrate noted for the 1970-71 season was not as pronounced for the 1971-72 season.

The deposit of avalanche material was exposed to much of the direct solar radiation during the daylight hours. Due to its depth and high density, it was instrumental in contributing to the runoff during the major melt period as well as late into July when the last of the deposit finally melted and the flow ceases. On the recession portion of the hydrographs it can be seen that both the actual flow and the flow per unit area is larger for the north cirque for much of this period. This increased runoff is believed to be due primarily to melt of the avalanched material.

The estimated error associated with the seasonal runoff values for the two cirques was computed in the same manner as described for the previous season. It is somewhat of a guess, yet believed to be larger than the actual value.

From the basic data shown in Table 7, it would appear that the management effort did have some effect on the runoff from the study area. The main effects, however, are not readily apparent in the data as present in Table 7 and thus will be discussed separately in a later section.

Evaporation Potential

One of the hypotheses made concerning the anticipated results of the management effort was that the avalanched material would be relocated in an area of reduced evaporation potential with a reduced evaporative surface. This combined effect of reduced surface area and reduced potential should result in an overall reduction in the evaporative losses and thus an increase in the runoff.

In the review of literature, it was seen that many of the evaporation equations were of the form:

$$E = K\,(AH - SH)\,WS$$

in which

E is the evaporative loss

AH is the absolute humidity of the air

SH is the absolute humidity of the evaporative surface

WS is the wind speed, and

K is a constant relating the measured quantities.

Various researchers have chosen to base these similar relationships on various time periods, as well as data measured at different locations relative to the evaporative surface. In view of the differences between the various relationships presented in the literature, it was decided to base this analysis on the simplest possible relationship. For this purpose the evaporation potential index will be used and is defined here as:

$$EPI = \sum_{i=1}^{8} (AH_i - SH_i)WS_i$$

in which

EPI is the daily evaporation potential index for a unit of surface area, AH is the average absolute humidity of the air for each 3 hour period during the day in mb.,

SH is the average absolute humidity of the snow based on the assumption that the snow surface is at the same temperature as the air when the air temperature is below 32°F, and at 32°F when the air temperature is above the freezing point, for each 3 hour period during the day in mb., and

WS is the average wind speed for each 3 hour period during the day in mph.

The values of the EPI for the feeder area and the cirques for much of the study period are shown in Fig. 23. The lines connecting the various values for consecutive days are not intended to represent the diurnal variation, but rather are merely intended to be an aid in tracing the fluctuations in the magnitude of the daily totals. It can be seen that several times during the winter the data for the feeder area was not available, yet sufficient data are presented to observe the general difference between the two locations. In Fig. 23, it can be seen that the value of the index for the feeder area was almost always greater than that for the cirques, with this difference often being as much as an order of magnitude. It is also seen that for much of the period extending for the time of the major melt on, the value of the index for the cirques was negative, indicating condensation on to, as opposed to evaporation from, the snow. Since the avalanche deposit was still present throughout this period, the relocation into the cirques represents not only a reduction in the potential loss that would be expected at the ridge location, but also a potential source for additional runoff resulting from the condensed water vapor indicated by the negative potential of the cirques.

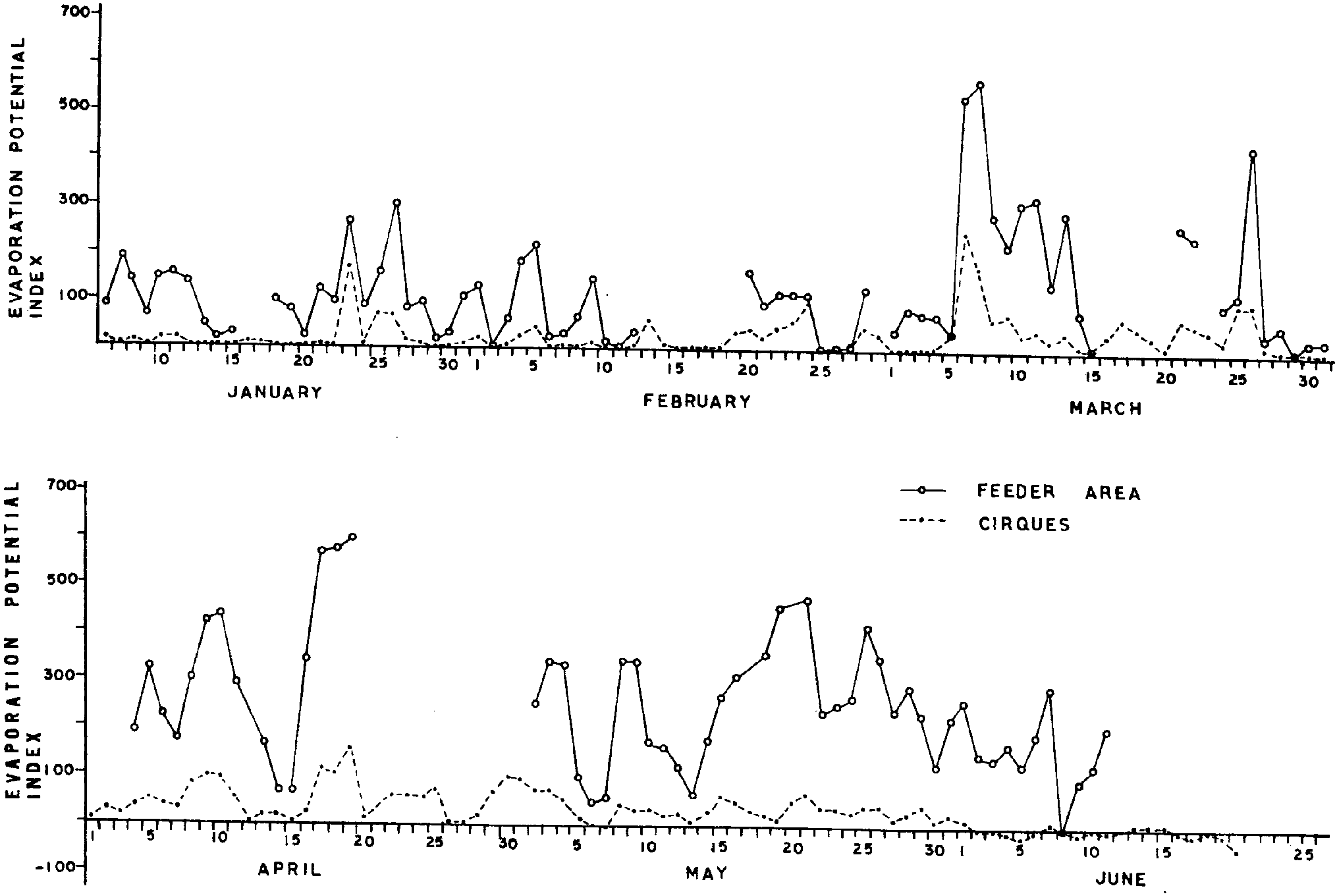


Fig. 23 Daily values of the evaporation potential index (EPI) for both the feeder area and the cirques, 1971-72 season.

The affect of the avalanching on reducing the effective surface area is somewhat more difficult to determine. The surface area of the deposited material was readily estimated at 74,000 square-feet. However, the surface area that this material may have had if it had been left to form naturally is almost impossible to estimate. Obviously, it is not the sum of the surface area exhibited by each of the cornice deposits prior to avalanching, approximately 165,000 square-feet. Nor is it the maximum surface area exhibited by any one of the avalanche efforts, approximately 55,000 square-feet. If it is assumed that the material would have been deposited at a uniform density equal to the average density of the cornice deposit and distributed equally over the entire length of the ridgeline in the form of a square cross-section with two sides as the effective surface area, a value of approximately 80,000 square feet is obtained. These values all assume that the entire avalanche deposit originated as cornice material and do not include effective surface area of the windslab or sidehill, both of which were influential in contributing to the avalanche deposit. If one were to include even the first 50 feet of slope below the cornice deposit as a part of the effective evaporation surface, a minimum value of over 80,000 square feet is obtained. When these figures are compared to the maximum surface area of the deposited material, which resulted after the fourth avalanche, it can be seen that there was a reduction in the surface area of the deposits brought about by the management effort. When these findings are combined with the results presented previously concerning evaporation potential, it can be seen that the hypothesis concerning the effect of the avalanching on evaporation is substantiated.

Effects of the Management

The discussion presented in the early parts of this paper indicated that an increase in the catch efficiency of the cornice deposits was anticipated as a result of the management effort. Due to the potential error associated with the transport out of the feeder area during each of the sub-periods, as well as the uncertain nature of the magnitude of this error, no definite statement concerning the effect of each individual avalanche will be made. Merely for comparison purposes, the catch efficiency for each of the sub-periods on both cirques has been presented in Table 8. The error shown is that obtained from the individual errors as indicated in the previous discussions. When the seasonal values are considered, it can be seen that even with the potentially large error estimates used, the indicated difference in seasonal catch efficiencies for the two cirques is greater than the potential error. It must therefore be concluded that the management effort did have some effect on the seasonal catch efficiency of the cornice deposit. Further support to the statement concerning the effect of the management effort can be obtained by first assuming there was no effect and that the seasonal catch efficiencies of the two cirques were the same. When this is done, the volume of water that would have been stored in the cornice on the north cirque can be calculated. The volume so calculated is within 5 per cent of the measured volume remaining at the end of the winter period. If the management effort had no effect, which is the assumption under consideration, where did the 16.2 ± 0.3 acre-feet of water stored in the avalanche deposit come from. Admittedly such computations have large potential errors which cannot be determined from the

TABLE 8

Catch Efficiency of the Cornice Deposits

For Period Ending	11-18	12-03	1-07	1-31	2-18	3-08	3-22	4-05	4-24	Season
NORTH CIRQUE										
Total Transport in ac.-ft.	5.69	10.76	11.71	24.95	3.21	19.00	1.77	7.52	21.00	105.69
Possible Error in ac.-ft.	1.53	2.04	3.00	4.34	6.31	7.81	6.32	8.36	6.18	5.24
Change in Cornice Storage in ac.-ft.	4.00	5.47	3.18	13.69	1.03	3.11	1.53	3.41	3.58	38.99
Possible Error in ac.-ft.	0.21	0.30	0.26	0.26	0.25	0.22	0.11	0.60	0.72	0.41
Catch Efficiency	0.70	0.51	0.27	0.55	0.32	0.16	0.87	0.45	0.17	0.371
Possible Error	0.12	0.04	0.03	0.08	0.21	0.04	0.60	0.20	0.01	0.015
SOUTH CIRQUE										
Total Transport in ac.-ft.	7.52	12.97	13.95	26.94	3.42	19.95	2.06	7.73	28.47	123.01
Possible Error in ac.-ft.	2.02	2.46	3.58	4.68	6.74	8.16	7.37	8.59	8.39	6.10
Change in Cornice Storage in ac.-ft.	5.10	6.63	3.77	6.51	0.55	2.96	0.31	1.24	1.31	28.38
Possible Error in ac.-ft.	0.34	0.39	0.34	0.38	0.56	0.55	0.40	0.81	0.82	0.30
Catch Efficiency	0.68	0.51	0.27	0.24	0.16	0.15	0.15	0.16	0.05	0.231
Possible Error	0.11	0.06	0.04	0.02	0.06	0.02	0.08	0.04	0.03	0.009

data. However, the assumption that there was no effect is believed to be an unrealistic one and not supported by the data.

The indicated increase in the seasonal catch efficiency of the cornice deposit is not the sole potential source for the observed difference in runoff from the two cirques. The potential errors have been discussed in the previous sections and as was seen do not fully explain the differences. It is believed that some insight into the possible relative importance of the catch efficiency and evaporation potential can be obtained from further analysis of the water-budget for the cirques. Since the errors have already been considered, and further, since it is the relative values and not the actual magnitude of the numbers which are to be considered, the discussion of errors will be limited to the main points under consideration.

The water-budget analysis for the entire runoff period can be divided into two parts, that resulting from the melt of the main snowpack, and that resulting from the late melt of the cornice deposits. On 24 June it was observed that the snowpack in the cirques had all melted except for a few isolated deposits where drifting had been observed during the winter. Thus it will be assumed that this date marks the end of the main melt period and forms the division for the two parts of the analysis. It can be seen in Fig. 21 that this condition was not as well defined on the runoff hydrograph for the 1971-72 season as it was during the previous season, Fig. 14. However, the conclusions based on the analysis performed by using this date, or some other, varied by as much as a week, are basically the same.

The main components of the water-budget analysis for this period of early melt are shown in Table 9. Here, two items are considered

TABLE 9

Water-budget for Early Melt in the Cirques

	South		North	
Snowpack melt in acre-feet (assumed 98% complete)	31.8	±2.61	26.0	±2.18
Change in cornice storage in acre-feet	11.2	±0.36	22.1*	±0.54
Precipitation during period in acre-feet	4.5	±0.07	3.9	±0.06
Total water available for runoff in acre-feet	47.5	±2.64	52.0	±2.25
Remaining cornice storage in acre-feet	17.2	±0.32	16.9*	±0.36
Runoff to date (0^h 24 June)				
in acre-feet	30.2	±1.31	31.3	±1.40
in inches	9.3		15.1	
Losses in acre-feet	17.3	±2.95	20.7	±2.65
in per cent	36.4	±6.0	39.8	±5.1
in inches/acre of cirque	7.2	±1.2	10.0	±1.2

*Includes avalanche material.

important. First, it is seen that the runoff per unit area on the north cirque is approximately 60 per cent larger than that on the south. This increase in runoff is believed to be due in part to the increased melt resulting from the avalanched material and also, in part, from an accelerated early melt of the cornice deposit. This accelerated melt is believed to be due to the nature of the underlying material as well as the effect of the winter blasting on the cornice formation. The blasting left the deposit highly fractured with numerous craters in the upper surface as well as cracks and crevices throughout most of the formation. These irregularities in the deposit must have had some influence on the rate of heat transfer from the surface into the lower reaches of the deposit and also provided additional avenues by which the surface melt could quickly leave the formation.

The second item of importance shown in the figures of Table 9 is that of losses and particularly the losses per unit area. The indicated difference of nearly 30 per cent may be the result of errors, the result of storage in the alluvial deposit on the north cirque, or possible increased evaporative losses occurring from the avalanched material which was deposited in a location which was exposed to the direct solar radiation for most of the day. In contrast, much of the snowpack on the south cirque was shaded either by the trees or the ridge on the southern boundary for much of the day. The actual cause for this difference is not known and is presented merely as a point of interest.

The results of a similar analysis performed on the late runoff are presented in Table 10. Although there was a portion of the

TABLE 10

Water-budget for Late Melt in the Cirques

	South		North	
Remaining snowpack melt in acre-feet	0.6	±0.5(?)	0.5	±0.5(?)
Precipitation during period in acre-feet	1.6	±0.02	1.4	±0.02
Change in cornice storage in acre-feet	8.0	±0.38	1.6	±0.43
Change in avalanche deposit in acre-feet	--		8.6	±0.18
Total water available for runoff in acre-feet	10.2	± .6(?)	12.1	±0.7(?)
Remaining cornice deposit in acre-feet	9.2	±0.18	6.7	±0.12
Runoff during period in acre-feet	5.7	±0.15	8.0	±0.21
Losses in acre-feet	4.5	± .6(?)	4.1	±0.7(?)
Assuming ALL runoff came from the melt of the cornice and avalanche deposits				
Water available for runoff in acre-feet	8.0		10.2	
Runoff in acre-feet	5.7		8.0	
Losses in acre-feet	2.3		2.2	

available water which originated as regular afternoon showers, there was generally no noticeable effect of these in the runoff hydrographs (Fig. 21). The one increase observed in the runoff resulted from a moderate summer storm which is not typical of the general afternoon shower condition. If it is assumed that these afternoon showers did not contribute significantly to the runoff, and thus the main source of the runoff was the melt from the cornice deposits, the values shown in the lower portion of Table 10 are obtained. Here it will be seen that the losses which occurred during the latter runoff period are basically the same for the two cirques. However, when the remaining cornice deposits which do not contribute to the runoff are considered, the losses on the south cirque are somewhat larger.

The three water-budget analyses presented in Tables 7, 9, and 10 all suggest that there was basically no difference between the observed losses on the two cirques. Since it was hypothesized that the management effort would increase the runoff by increasing the catch efficiency of the cornice deposit and reducing the evaporative losses, the similarity of losses could be interpreted as meaning that the whole effect of the management effort was the result of the increased catch efficiency of the cornice deposit. This conclusion is believed to be incorrect. The volume of water per unit area remaining in the cornice deposits at the beginning of the melt season was basically the same for the two cirques. The volume of water per unit area remaining after the runoff from the cirques had stopped was also basically the same. Since there was no increase in the volume of water stored in the ridgeline deposit as a result of the management effort, there can be no increase in runoff resulting solely from the indicated increase in the catch efficiency of the cornice deposit. Furthermore, since there was no increase in the ridgeline deposit, the effect that such an increase might have on the runoff cannot be obtained from this study.

An estimate of the relative importance of the two factors anticipated from the management effort can be obtained from assuming that the unit losses from the ridgeline deposits on the two cirques are the same. Since the initial unit volume and final unit volume on each of the deposits were basically the same, the assumption of equal unit losses seems reasonable. The validity of this assumption, however, cannot be directly tested from the data.

If it is further assumed that the coefficient in the evaporation equation expressed in the conventional form suggested by Dalton is a constant for both the cirques and the feeder area, then an estimate of the importance of the relocation process in reducing losses, and thus increasing runoff, can be obtained. These assumptions can be expressed as:

$$\text{Total observed loss} = \text{Cornice loss} + \text{Cirque loss} \tag{1}$$

in which

$$\text{Cornice loss} = k_1(\text{EPI})_1 \times \text{Cornice area} \tag{2}$$

$$\text{Cirque loss} = k_2(\text{EPI})_2 \times \text{Cirque area} \tag{3}$$

$$k_1 = k_2 \tag{4}$$

and

Subscript 1 refers to the feeder area and

Subscript 2 refers to the cirque area.

EPI is the evaporation potential index as previously defined.

In the foregoing relationships, the units of the evaporation potential index are accounted for in the units of the constant, k, and thus, for simplicity, will be omitted from the discussion. When the losses are expressed in terms of acre-feet of water and the areas in terms of acres, the units of k are feet of water per acre of surface per unit of evaporation potential index. If the relationship of Eq. 1 is applied to the data obtained on the south cirque for the period of melt from the main snowpack, i.e., Table 9, the following is obtained:

$$E = 0.0037\ (EPI) \tag{5}$$

in which

E is the average daily loss in inches per unit area assumed to be the result of evapo-sublimation, and

EPI is the daily evaporation potential index as previously defined.

By applying the relationship of Eq. 5 to the cornice deposits on both the south and north cirques, and assuming that the evaporation potential index as computed for the feeder area was representative of that encountered by the cornice deposit throughout the entire period of the early melt, an indicated loss of 8.1 acre-feet is obtained on the south cirque while 6.1 acre-feet is obtained for the north cirque. When the observed changes in the cornice storage are compared to these indicated losses, 11.2 (±0.4) and 8.1 respectively on the south cirque, and 14.5 (±0.4) and 6.1 respectively on the north cirque, it can be seen that approximately half of the indicated change in storage could have been the result of evaporative losses. The apparent difference between the comparisons on the two cirques is probably the result of the increased early melt on the north cirque attributed to the disturbances left in the deposit by the blasting.

When the data from the water-budget are combined with the estimates of the evapo-sublimation loss several inferences can be made concerning the possible effect of the management effort. First, it can be seen that for both the managed and unmanaged cornice deposits approximately 30 per cent of the water remained in the deposit after the summer runoff from the cirques had ceased. When the actual values are considered, 29.4 (±2.0) per cent on the managed north cirque, and 32.0 (±1.8) per cent on the unmanaged south cirque, it can be seen that the management had no apparent affect on the remaining deposit. Since this management scheme which was aimed at reducing the size of the ridgeling deposit and had no effect on the portion of the deposit remaining, it is reasonable to assume that the proportion remaining from a scheme aimed at increasing the size of the ridgeline deposit would be at least as large as the indicated 30 per cent. It should be remembered that this remaining deposit is not carried over to the next season, but rather continues to melt and evaporate until the entire deposit had disappeared.

If it is further assumed that the analysis for estimating the losses from the ridgeline deposit during the effective melt period is reasonable, then approximately one half of the noted change in the storage of the deposit was lost. When this value is combined with the 30 per cent remaining after the effective runoff period, it is apparent that approximately 65 per cent of the ridgeline deposit was not available for useable runoff. The magnitude of the error associated with such an estimate can not be calculated from this data, yet if it is assumed that the values on the evaporative loss are in error by as much as ±50 per cent, there would still be only half of the ridgeline deposit which would be available for runoff.

A relative comparison of the effect of the relocation of the ridgeline deposit in the cirque can be obtained by assuming the estimated evaporative losses from the ridgeline deposit are reasonable. In essence, this is the same as assuming that the relationship developed in Eq. 5 is reasonable. The losses from the cirque deposits can then be estimated and thus separated from the total measured loss. When this is done, the value for the estimated loss on the north cirque is 18.6 acre-feet while that on the south is 14.0. In terms of the water available for runoff, these quantities represent 26 and 21 per cent, respectively. Thus as a first approximation, it can be seen that the relocation in the cirques yields about 75 per cent of the stored water as useable runoff. Again, there is no means of accurately determining the error associated with this estimate. The values presented are merely for comparitive purposes.

Comparison of the Study Period to Normal Conditions

The short study period on which the results of this study are based leaves one question still to be answered. Namely, are the indicated results the affect of the management effort, or are they the affect of some abnormal weather condition? Since a historical record for the study area does not exist, records from the surrounding areas will be used in this analysis. The three main items which could affect the indicated results are those of seasonal precipitation, seasonal runoff, and wind conditions in the feeder area.

The degree of normality associated with the seasonal precipitation can be determined from the records obtained at HAO. The recorded values for the 1970-71 and the 1971-72 season were 14.56 and 12.15 inches, respectively. By using the period from 1952 through 1972 as a basis for comparison, the mean and the standard deviation of the seasonal precipitation, i.e., November through May, are 13.15 and 2.57 inches, respectively. It can be seen that the precipitations for the study periods were within less than one half of the standard deviation of the mean and must be considered as being normal. It is, however, interesting to note that the water-budget analyses are based on a period for which the precipitation was less than the mean value.

The runoff from the Columbine Ditch was used as the basis for the comparison on the seasonal runoff values. The location of this transmountain diversion can be seen in Fig. 1 while the runoff relationships as compared to the HAO precipitation shown in Fig. 2. For the period from 1952 through 1972, the mean and the standard deviation for the seasonal runoff are 1470 and 430 acre-feet, respectively. When these values are compared to the values for the two years of the study period, i.e., 2160 and 1790 acre-feet, respectively, it can be seen that the runoff for the study period was somewhat higher than the mean value. Further examination of Fig. 2 shows, however, that the observed conditions are not abnormal when considered in terms of the conditions for the last 10 years. The data presented in Fig. 2B suggests that there has been an increase in the runoff coefficient during the last 10 or so years. An answer will not be proposed as to whether this indicated increase is the result of improvements made in the ditch, the result of the weather modification studies being conducted in the region, or some other factor. All items mentioned could cause the indicated condition and are merely presented as a possible suggestion for the differences.

A historical record of wind data for the general location of the study area was not available. There was, however, a short record of wind data used in other studies being conducted by the C.S.U. Department of Atmospheric Sciences. The record used for the comparison is that referred to as the 700 mb. interpolated wind for Climax and is based on radiosonde data obtained twice a day at Denver, Colorado; Grand Junction, Colorado; Lander, Wyoming; Albuquerque, New Mexico; and Windslow, Arizona. Although the record extends from 1958, the first two seasons, i.e., 1958-59 and 1959-60, as well as the 1962-63 and 1963-64 are incomplete and have not been included in the analysis. For each season the period from 1 November through 30 April was used. The wind direction data were grouped into intervals of 10 degrees beginning with 0 degrees, while the wind speed data were grouped into two meter per second intervals. The frequency distributions for each season were computed and the distributions for the wind direction data and the wind speed data shown respectively in Fig. 24 and 25. In Fig. 24 it can be seen that no significant difference in the wind direction is noted for the two year study period. When the seasonal values shown in Fig. 24 are compared to the data for the feeder area shown in Fig. 15 it can be seen that the wind direction in the feeder area is controlled to a large degree by local factors. When the mean wind speed for the two seasons in the study period are considered, it

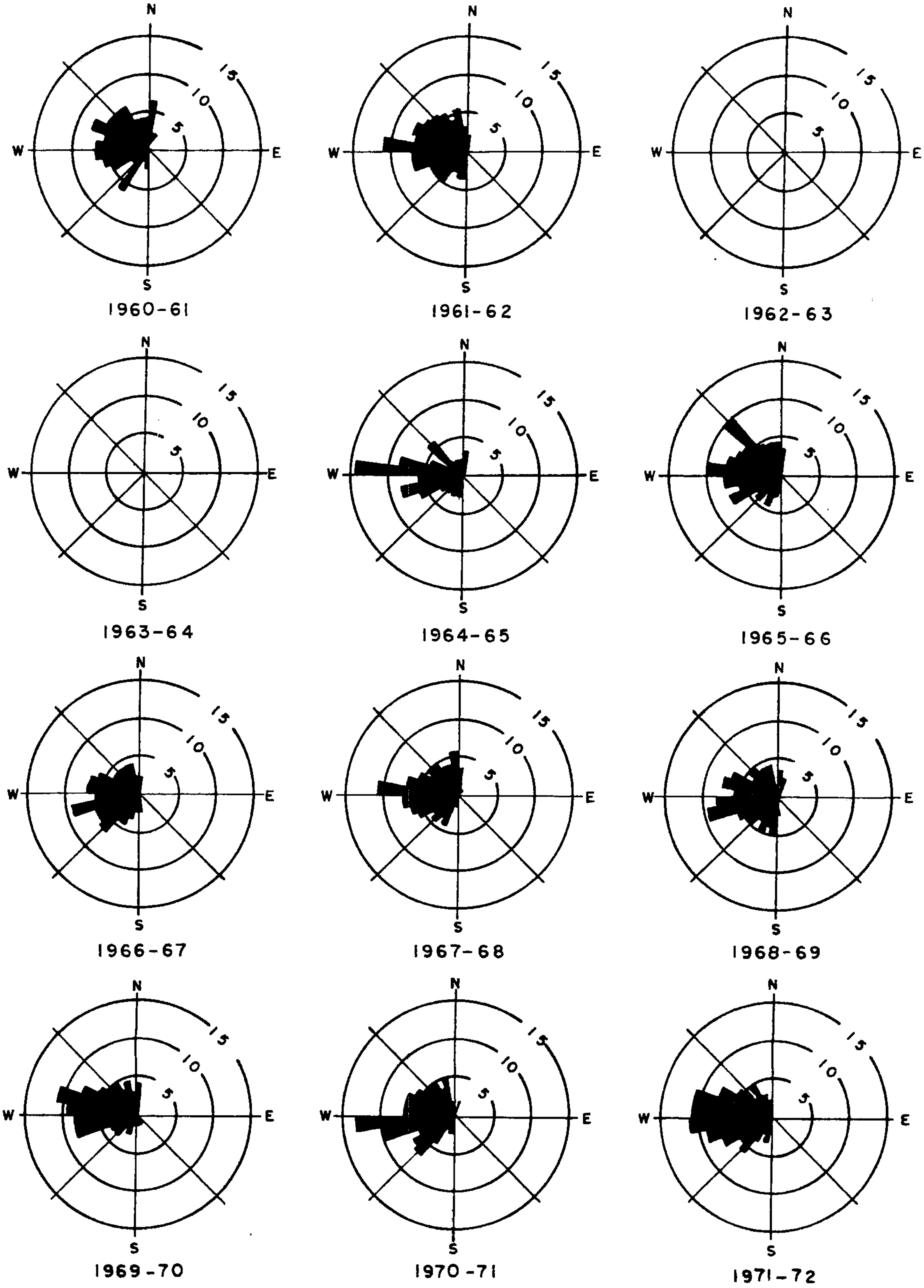
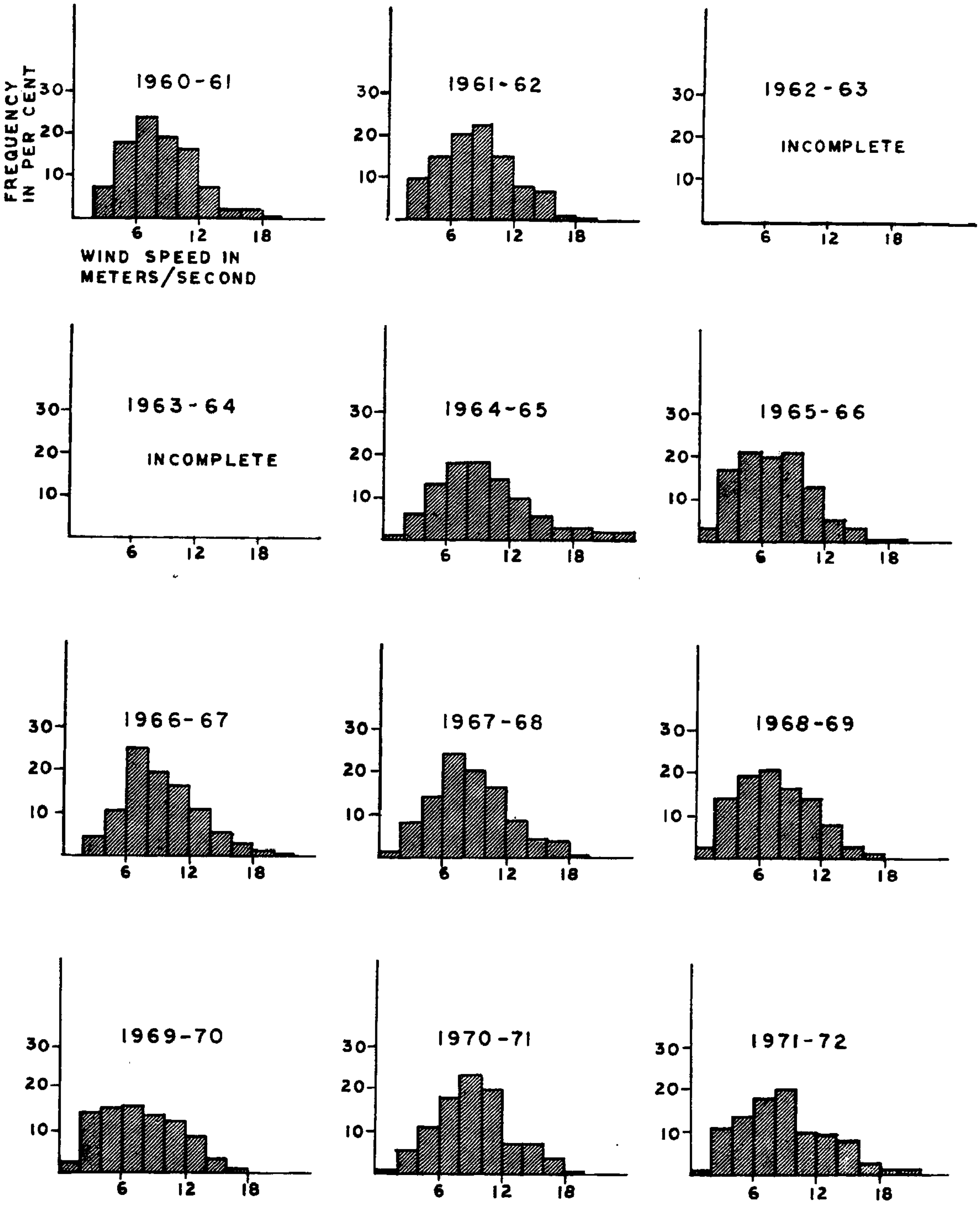


Fig. 24 Seasonal frequency distributions of the wind direction for the 700 mb. interpolated winds for Climax, Colorado. Each season is from 1 Nov. through 30 April.



NOTE: The axes used on all graphs are the same as those indicated on the one in the upper left position.

Fig. 25 Seasonal frequency distributions of the wind speed for the 700 mb. interpolated winds for Climax, Colorado.

would appear that the values of 8.92 and 8.64 meters per second are not significantly different from the mean of the seasonal values, 8.12, which had a standard deviation of 0.86.

The seasonal values, however, do not fully represent the data. When the monthly distributions of wind direction are considered, the variations between the same month for different years is as great as the difference between the seasonal values shown in Fig. 24. The monthly mean wind speed, however, shows a condition not apparent in the values shown in Fig. 25 and have been listed in Table 11. Here, it can be seen that the monthly mean wind speed for January 1972 is larger than that for any other January in the data set. Furthermore, of the 60 months listed, the value for January 1972 is the second highest exceeded only by December 1964. When the values for February, March, and April of 1972 are considered it can be seen that they also are greater than the mean values for these respective months. It must therefore be concluded that the winds during a portion of the primary study period were greater than the normal values and may have had some influence on the data analysis. The magnitude of this influence cannot be determined from the data, yet is believed to be sufficiently small that its affect will not alter the basic conclusions.

TABLE 11

Monthly Mean Wind Speed Data for the 700 mb. Interpolated Winds for Climax, Colorado

(All Values are in Meters per Second)

Season	Nov.	Dec.	Jan.	Feb.	March	April
1971-72	7.79	7.50	11.37	8.57	7.98	8.23
70-71	9.32	9.98	9.93	7.89	8.76	6.56
69-70	6.84	7.44	8.31	6.61	6.44	7.97
68-69	6.87	9.79	8.73	6.43	6.02	5.80
67-68	8.47	9.66	7.00	8.41	5.85	7.47
66-67	8.60	7.24	10.72	10.10	9.33	10.20
65-66	7.66	7.57	7.18	6.71	7.40	6.37
64-65	6.34	13.70	9.11	8.46	8.05	8.03
63-64	data incomplete					
62-63	data incomplete					
61-62	8.46	9.62	9.44	9.46	7.11	6.93
60-61	7.84	7.65	7.49	7.79	8.18	8.50
Mean	7.82	9.01	7.90	8.04	7.53	7.61

Chapter VIII

A MANAGEMENT TECHNIQUE AND ITS EVALUATION

The discussion presented in this chapter is based, in part on the data presented previously as well as numerous field observations and analyses. Most of these field observations cannot be substantiated by measured data, and as such, they represent more "the art," than "the science" of engineering. This chapter is presented as an engineering analysis of a problem in which the analysis is based not only on factual data, but also simple observations and deductive reasoning. No attempt will be made at placing error limits on all values used. The errors have, however, been considered in the overall development process.

Considerations Imposed on the Selection of a Technique

The data presented in Chapter VII indicated that over 700 acre-feet of water was transported out of the feeder area. If it is assumed that the major portion of this was carried by the wind over the ridgeline, then as an estimate there was 600 acre-feet of water/mile transported over the ridge. If it is further assumed that this water has a value equal to the present rate for irrigation water in northern Colorado, i.e., $22/acre-foot, the transport from the study area had a value of approximately $16,000 or $14,200 per mile of ridgeline. Assuming the same figures hold for all of the Chicago

Ridge, the transport from the nearly 11 miles of ridge represent over $150,000.

The total transport from the ridge was not all lost from the useable runoff. The values previously presented, Table 6B, suggest that about 20 per cent of the transport was caught in the natural cornice formation. From the discussion on losses occurring from the ridgeline deposit, it was estimated that at least half of the cornice storage was lost to the useable runoff. The total losses from the transport and ridgeline deposit are thus equal to about 540 acre-feet of water per mile of ridgeline and represent the potential return from a management effort. This volume of water has a value of approximately $12,000 per mile of ridgeline. This potential, however, cannot be realized in an actual system as it assumes 100 per cent efficiency. It is merely a goal for which to strive.

Knowing the goal, what scheme or schemes offers the greatest potential return within the imposed constraints. Here, the constraints set forth in Chapter III will be used. With these constraints, the use of structural devices for increasing the catch of the ridgeline deposit is not a feasible solution. Such devices are excluded, not because of their engineering feasibility, but rather because they are "unsightly" in the eyes of the public. This constraint is believed to offer the greatest limitation to an effective management effort, yet must be accepted as a realistic condition. In view of the constraints and the data presented previously, it is believed that the periodic removal of the ridgeline deposits offers the greatest return. The procedure tested in this study, however, is not the optimal technique for all locations.

The Management Technique

The basic technique involved the periodic removal of the ridgeline deposit with the removed material being relocated in the cirques. If it is assumed that the catch efficiency of the early ridgeline deposits are of the order indicated in Table 8, then these small deposits would trap roughly 70 per cent of the transport from the feeder area. If the removal could be carried-out efficiently on a regular basis, it is reasonable to assume that the catch efficiency of the deposits could be held at this high value throughout the entire winter. The potential value of the water that could be realized from such an operation would be roughly $10,000 per mile of ridgeline treated. There will, of course, be losses from the deposits relocated in the cirques which will reduce this value by 25 to 30 per cent. The losses from the cirques are based on the discussion presented previously as well as consideration of the observed runoff in the Columbine Ditch and the suggested water available from the snow survey measurements.

The actual scheme used for the removal of the deposit will depend on the general topographic features and deposit characteristics at each site location. These have been discussed in Chapter VI and will be considered here only in terms of how these conditions might effect the management scheme.

Various Removal Schemes

The number of possible removal schemes that might be effective at relocating the ridgeline deposit in the cirques is quite large and limited only the imagination of the person performing the consideration. These schemes can be grouped into several main categories, some of

which are considered here. This presentation is in no way intended to present all of the possible schemes. It does, however, present a representative sample from which further development and consideration can be invisioned.

Explosives. The use of explosives to remove the deposit is considered to have a limited use when the frequent removal of the deposit is desired. If the catch efficiency of the deposit is to remain high, the removal must be performed before the deposit reaches the stage shown in the schematic drawings of Fig. 10C and preferrably when it is in the stage indicated by 10B. For such stages of development with the upslope cornice having the ridgeline separated from the crest of the cirque, the use of explosives for the removal is not suggested. The main problem encountered is that much of the deposit is resting on the upper portion of the slope. In such regions the slope is not sufficiently steep to allow the material to slide once it has been freed by the explosion.

The locations where the ridgeline and the crest of the cirque coincide are much more suited for the use of explosives. It is interesting to note that all locations in the study area where this condition was observed, there was also a downslope cornice formation. The experience gained from the blasting experiments suggests that more effective removal is obtained when the charge is placed closer to the slope. This condition helps to reduce the absorption of the shock by the snow deposit. There is also evidence to suggest that the line charge is more effective than the point charge. In either case, it was found that a greater efficiency could be obtained by first concentrating on the removal of a key section of the deposit and then

working in both directions from the remaining void. These deposits often have the shape of an arch and, as such, to try and remove the entire formation at one time means overcoming the arching effect of the deposit as well as its natural adherence to the slope.

One of the greatest problems encountered with the use of explosives was the placement of the charge. Much of this difficulty can be attributed to the size of the formation and the lack of mechanical equipment for the boring process. One scheme which seems to be a reasonable solution to this problem is the use of paper tubes placed on the side hill before the winter season begins, as well as after each blasting event. The tubes would be capped on both the top and bottom, with the upper cap being made in such a way that it can be easily removed. The tubes must also be made sufficiently strong that they will not collapse under the weight of the deposit and be placed in such a way that they will protrude from the formation at the time that blasting is desired. When the blasting is to be performed, the temporary caps would be removed, the charge placed in the tube, well tampted and sealed. When a series of such charges have been prepared, they could be detonated either by electric or conventional blasting caps. There are, however, several problems which could result from such a procedure. First, if the tubes were improperly tampted, they would act similar to a cannon and merely blast the tampted material out the top. Once airborn, this material would be a projectile aimed at some down range target. The second possible problem with the use of the tubes is that they will be destroyed by the blasting and provide litter on the entire upper slope. If care is used in the selection of the material from which the tubes are constructed, this problem could be easily corrected.

There are several problems involved with the use of explosives which must be considered. Although not used in this study, an approved storage magazine in the general location where the blasting is to be performed is considered a necessity. The problems encountered by trying to haul the needed explosives into the area each time the blasting is performed are not justified by the added expense of placing the magazine in the blasting area. When explosives are used, it must be expected that some of the material will not ignite and thus remain on the side hill representing a potential hazard during the summer months. The ever present danger associated with explosives must also be considered as well as the additional regulations and liabilities imposed by state and federal agencies.

Mechanical Removal. The regions where the ridgeline and the crest of the cirque are separated by some sizeable distance are well suited for the use of mechanical removal techniques. At one such location in the study area, this separation was almost 70 feet and, as such, less than 25 per cent of the mature formation could be removed by the avalanching techniques. If, however, a small bulldozer had been used to push the material over the crest of the cirque, a much greater return would have resulted. There is a hazard with using some device such as a bulldozer to remove the material. If the location of the cirque crest is not readily apparent and well marked, it is possible for the operator to drive over the edge. With the use of proper safety precautions this procedure should be no more dangerous than boring and blasting the leading edge of the cornice formation.

In some locations the use of mechanical scrapers operated by remote winches and pully arrangement may prove satisfactory. Such installations, however, may require the installation of permanent structures which would make their use unsuited as this would violate one of the imposed constraints.

Other Schemes. Removal schemes such as the use of large mirrors to concentrate the solar radiation onto a small area and melt the deposit, the use of electric heating coils or laizers to melt the deposit, and even the placing of heating pipes just under the ground surface have all been suggested. Needless to say, such schemes are economically unfeasible. There is, however, one other idea which possible might work. Instead of relying on some scheme to remove the material, is it possible to alter the slope in such a way that the frictional resistance to sliding is smaller than the gravitational component parallel to the slope. If this could be done, the material which settles on the slope would naturally slide off and come to rest in the sheltered cirque. It has been suggested that this might be accomplished by covering the upper slope with a sheet of thin plastic. The main problem associated with this idea is the physical one involved with the placement and holding of the plastic sheet. In some regions of the study area, the placement could be performed after some preparation of the slope. However, the problem of holding such a sheet in place under strong wind conditions has not yet been fully considered. It may be that some of the new synthetic rubber materials presently being used as lining material for irrigation ditches would be better adapted for this purpose than is the thin plastic sheet. In either case, the scheme should be considered as a feasible solution worthy of further study.

Economic Considerations

One of the main parts of any management scheme is that of cost and return. A direct comparison between the costs associated with a research effort, such as this one, and an operational procedure is not possible. However, sufficient information is available for a reconnaissance level benefit-cost comparison. Here, it will be assumed that the operation is aimed at keeping the deposit as small as physically possible, and thus keeping the catch efficiency of the deposit near its maximum. The consideration will be for the entire length of the ridgeline in the study area relying on the use of explosives for removing the deposits where the ridgeline and cirque crest coincide and a small bulldozer in the areas where applicable. It will further be assumed that all materials necessary for the management effort have been stored in the immediate area and are available for use when needed. This latter assumption greatly reduces the time and expense involved in the winter operations. The final assumption, that favorable weather conditions exist when the management effort is attempted, is impossible to control. The data from the past two years indicates that in general the management effort could be performed at least one day a week provided the staff and equipment were in the area and readily available. Based on these assumptions, the results of this cost analysis are shown in Table 12.

TABLE 12

Preliminary Benefit - Cost Comparison for the Proposed Management Technique

COSTS:		
Bulldozer and operator - $100/day for 20 days per year		$ 2,000
Blasting crew - 3 men total of $100/day for 30 days per season		3,000
Explosives - 10,000 lbs. at $50/100 wt.		5,000
Rental on drilling rig		1,000
Carbon black to melt resulting deposit in cirques		500
Miscellaneous costs		1,500
	Total Costs	$13,000
RETURN:		
Based on: 700 ac.-ft. of transport 60 % catch efficiency 25 % losses in the cirques		
	Expected runoff	315 ac.-ft.
Natural deposit 700 ac.-ft. of transport 23 % catch efficiency 70 % seasonal losses		
	Expected runoff	48 ac.-ft.
	Net increase	267 ac.-ft.
BREAK-EVEN VALUE OF THE WATER:		$48.75/ac.-ft.

Here it can be seen that the break-even value of the water from an efficient operation is \$48.75/ac.-ft. which is twice the present market value.

This reconnaissance level analysis indicates that the technique is not comparable to present sources of water. However, it is not what might be considered as economically unfeasible. With additional research, it is possible that costs can be further reduced and a favorable benefit-cost ratio obtained.

Chapter IX

SUMMARY AND CONCLUSIONS

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 procedure 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 managed 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 overall effect of the management effort.

Based on the field observations and the results of the above analyses, a management technique was indicated and evaluated.

Based on these analyses, the following conclusions have been reached:

1. Approximately 20 per cent (21.7 ± 3.9%) of the seasonal precipitation in the feeder area remained in the snow pack 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 per cent (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 snow cover 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 per cent 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 per cent, is believed to have sublimated from both the inplace snow cover 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 in place 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 snow cover, a total of only 39.9 ± 4.4 per cent 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 per cent, 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 per cent 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 useable 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 per cent 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 per cent 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 efficience of the ridgeline deposits, the deposit should be removed whenever the primary separation zone becomes filled with deposited material. This condition is represented by the condition shown in Fig. 10B.
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.

Chapter X

SUGGESTIONS FOR FURTHER STUDY

Many alterations and modifications in the operational procedure associated with the data collection and analysis from this study have been indicated. These are, however, of an internal nature and as such will not be elaborated on here. There are also numerous areas of further research suggested by this study which fall beyond the scope of the present investigation. Some of these are presented below.

1. Wind tunnel studies. The field observations suggest that the primary circulation is a part of a much larger secondary flow confined to the air space between the various ridges. If, through the use of wind tunnel studies, this can be shown to be true then further support to the findings concerning no valley transport can be obtained.

   If topographic effects on the upwind airflow are what really causes the various cross-section which were observed in the ridgeline formations, then they should be reproducible in the wind tunnel. The assumption of uniform transport from the feeder area can also be shown through wind tunnel studies. It was observed that the downslope cornice formation was more susceptible to soft slab avalanches, with this condition was attributed to overshooting of the secondary circulation. Through wind tunnel studies of the flow patterns, can this condition be substantiated, or is there some other cause not seen in variable field conditions?

2. Transport studies. Develop some type of field equipment to accurately measure the quantity of snow blowing over the leading edge of the cornice along the entire length of the deposit. By repeating the measurement performed in this study, and knowing the actual transport by the wind, the sublimation losses from the inplace and migratory snows can be obtained and separated. Furthermore, the conclusions concerning the amount of snow physically transport over the ridgeline, and thus the quantity available for management, could be substantiated by such measurements.
3. Evaporation in the alpine. There is evidence to suggest that the evaporative losses from the snow cover in the alpine is large particularly during the late winter and early spring. For example on the day of the last management effort, 24 April, it was possible to drive by snowmobile to the ridgeline without crossing bare ground in the early morning hours. By the end of the day bare ground existed nearly 300 feet down from the ridgeline on the west. The winds were less than 5 mph during the day, with clear skies and warm temperatures (max. 28°F). The water obviously was not transported out of the area by the strong winds, nor did it drain out as runoff from melt. It is believed to have sublimated. The magnitude of this sublimation can only be found through further study.
4. Runoff from the alpine. The data from this study suggested that there was approximately 20 per cent of seasonal

precipitation still in the feeder area at the end of the winter period. How much of this was realized as useable runoff? The results of such a study are far more reaching than might at first be indicated. If a weather modification program is claiming an increase in precipitation and yet most of this is lost, what is the net effect of such an operation? To view the problem from a different viewpoint, if an increase in runoff is noted from a weather modification program and yet none can be expected from the alpine regions, then the affect on the lower areas is much greater than suggested by the average value.

5. Factors affecting runoff. The variation in the simple runoff coefficient for the Columbine Ditch suggests that some factor other than seasonal precipitation is a major factor in determining the runoff. The range in the runoff coefficient from 0.67 to 1.64 cannot be attributed solely to errors. The data suggests that the missing factor in the analysis is the wind and the subsequent transport from the feeder areas. During periods of light winds there appeared to be a greater portion of the transport confined to the secondary circulations near the ridgeline. Thus possibly more deposition and less overall loss is occurring. If there is actually more water entering the cirques during light wind years than during strong wind years, this could account for the difference in runoff coefficients. The comparison, however, cannot be based on seasonal wind values. As was shown previously, the seasonal values can be misleading.

Possibly, the comparison lies with the wind velocities during the first transport period following the major precipitation events, or the major transport winds during the season, or some other factor not indicated by the seasonal values. Here again, far reaching results can be obtained from such a study. If a relationship could be developed and combined with the data from the Co-operative Snow Survey, a much better estimate of the anticipated runoff for the mountain states could be obtained.

6. Losses from the ridgeline deposit. Suggestions have been made that the ridgeline deposit is an inefficient place to store water. If a study was devised to actually measure the runoff from such deposits, as well as the losses, the relative importance of the catch efficiency and relocation processes suggested here can be determined. Such a study must give special attention to the magnitude of the potential error involved in the measurement, as it is anticipated that the runoff from the ridgeline deposit is of the same order as the error associated with the present study.
7. Improvements in the management technique. In the discussion presented in Chapter VIII some speculation concerning the probable effect of several management schemes is presented. Is the speculation correct? What other schemes might prove better? How can the drift formation be managed efficiently?
8. Ridgeline deposits and their control. The apparent differences between the work by Montagne, et al., and the observations resulting from this study suggest several areas

for further investigation. The effect of the local topography on the formation process is not fully understood particularly the effect of the upwind topography. The observation that soft slab avalanches are more prevalent in area of downslope cornices need further study to determine if this is a false conclusion biased by the study area. What controls the existence of the cornice or overhang? If this question can be answered, is there a way to cause, or prevent, the overhang?

Although there is some similarity between this suggested field study and the suggested wind tunnel study, it is believed that the two performed simultaneously would result in a much better understanding of the phenomena involved.

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APPENDIX A

DETERMINATION OF THE TRANSPORT OVER EACH CIRQUE

The determination of the transport over any given cirque would be quite simple if the wind direction and thus the effective feeder area remained constant with time. With the condition of the variable wind direction, an area which was at one time part of the feeder area for a given cirque may be part of the feeder area for a different cirque some time later. Since these changes occur quite rapidly and frequently, the possibility of sampling the snow pack for these short periods of constant wind direction and applying a water-budget to this short time period becomes highly impractical and often impossible in view of the data necessary and the time involved in obtaining these data. It is, therefore, desirable to have some procedure whereby a water-budget can be applied to the entire potential feeder area for a given cirque and from these data extrapolate an estimate of the transport over the given cirque. Two such procedures were developed and are presented below.

Procedure 1

The procedure developed is one that is simple and logical, yet does contain numerous assumptions. Some of the assumptions are not readily apparent during the development and will, therefore, be discussed in a separate section following the main development of the procedure.

The large area "A" shown in Fig. 26 represents that portion of Chicago Ridge which could under various conditions of wind direction

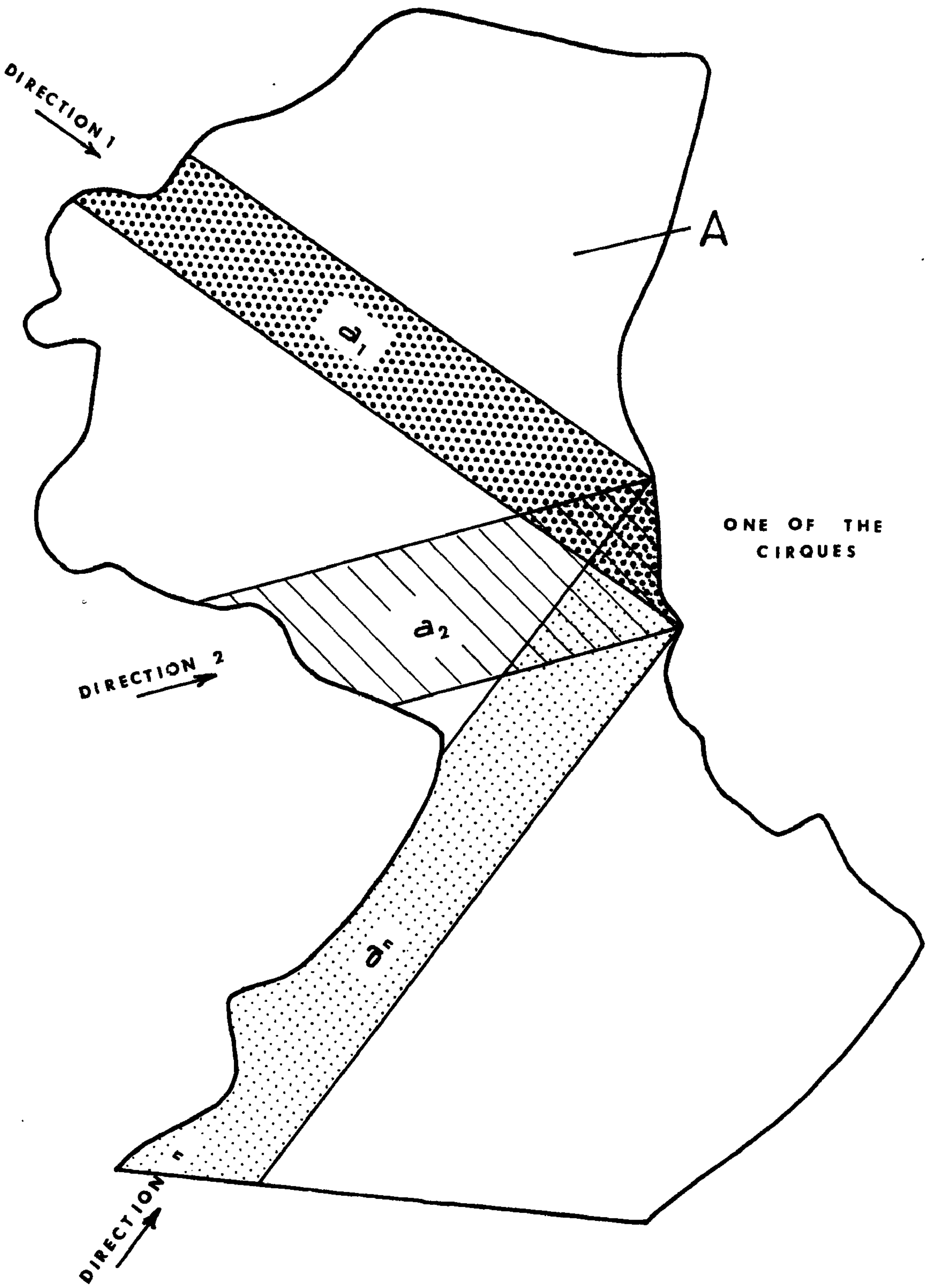

Fig. 26 Schematic diagram used in the development of Procedure 1 for the subdivision of the total transport into the portion which passed over each cirque.

contribute transported moisture into the cirques comprising the study area. This larger area "A" has previously been defined as the entire potential feeder area or simply the feeder area. For short periods where the wind is of a constant direction and velocity, such as direction 1 shown in Fig. 26, the effective feeder area for the given cirque is "a_1." When from direction 2, the effective feeder area is "a_2," and when from direction n, "a_n."

The mass of snow moved on the ridge in any time period, t_i, for which the wind is constant depends on the size of the feeder area, some function of the wind velocity, and the length of the time period:

$$MT_i = A\ f(V_i)\ t_i \tag{1}$$

When the wind is from direction 1, the movement on the entire ridge is;

$$MT_i = A\ f(V_1)\ t_1$$

and that in the cirque feeder area is;

$$mt_1 = a_1 f(V_1)\ t_1 \tag{2}$$

similarly for directions 2, and n;

$$MT_2 = A\ f(V_2)\ t_2 \qquad mt_2 = a_2\ f(V_2)\ t_2$$

$$MT_n = A\ f(V_n)\ t_n \qquad mt_n = a_n\ f(V_n)\ t_n$$

If a larger time period T is used such that $T = t_1 + t_2 + \ldots + t_n$ the total transport from the area "A" must be equal to the sum of the individual transports occurring during each of the smaller time periods, or;

$$MT_T = \sum_{i=1}^{n} A\ f(V_i)\ t_i \qquad (3)$$

In the same time period, T, the snow which left the effective feeder area for the cirque is given by:

$$mt_T = \sum_{i=1}^{n} a_i\ f(V_i)\ t_i \qquad (4)$$

Since for any given time period, t_i, for which the wind speed and direction are constant, the portion of the total transport which left the larger area through the cirque feeder area is given by:

$$PC_{t_i} = \frac{a_i\ f(V_i)\ t_i}{A\ f(V_i)\ t_i} \qquad (5)$$

the total portion for the time period T which left through the cirque feeder area is given by:

$$PC_T = \sum_{i=1}^{n} PC_{t_i} = \frac{\sum_{i=1}^{n} a_i\ f(V_i)\ t_i}{\sum_{i=1}^{n} A\ f(V_i)\ t_i} = \frac{\sum_{i=1}^{n} a_i}{nA} \qquad (6)$$

The mass transport from the total potential feeder area can also be found from the water-budget data as described in the main text and is given by:

$$MT_T = M_{beginning} - M_{end} + Precipitation_T \qquad (7)$$

The transport over any given cirque can then be found by combining Eqs. 6 and 7 to form the relationship given below:

$$mt_T = \frac{\sum_{i=1}^{n} a_i}{nA} \left[M_b - M_e + Prec_T \right] \qquad (8)$$

The relationship shown in Eq. 8 is far more involved than might first appear. The first assumptions made were those concerning the definition of the feeder area and have been presented earlier. The second assumption of major importance is that the transport from the entire potential feeder area is of a uniform nature and thus enables the formation of Eq. 5. The validity of this assumption cannot be directly substantiated as no attempt was made to measure the actual transport. In the discussion concerning the water equivalent of the snow cover in the feeder area it was noted that the average of the 39 snow survey samples was at times not representative of the actual volume of stored water due mainly to localized drifting. As seen from the data, this variation was quite small and, although not a direct measure, does give some insight as to the validity of the assumption of uniform transport.

Equation 5 is further restricted by the condition that it is limited to those periods when transport is occurring. If there is no transport from the feeder area the denominator of the equation is equal to zero and the percentage is thus undefined. This condition was readily corrected by noting the limiting wind speed at which transport occurred and then applying the analysis only to those periods where the actual wind speed was greater than the minimum transport velocity. The minimum transport velocity of 12 miles per hour was determined by numerous field observations of the wind speed at which noticeable transport could be detected. When the analysis of Eq. 8 was performed on both the entire set of wind data and only that portion of the data when the wind speed was in excess of 12 mph, the difference between the two values for any of the time periods used in the study was less than 5 per cent of the computed value. Considering the extreme case as presented here, i.e., no correction for the minimum transport velocity, it can be seen that this term offers a negligable error in the analysis.

Procedure 2

The second procedure was actually developed after the project had started and was used mainly as a check on the first procedure. The procedure, an attempt to synthesize possible transport conditions in the feeder area utilizes the wind data from the feeder area, the precipitation data from the feeder area, and the precipitation record from the HAO and Tennessee Pass stations, both of which are recording type gage.

The precipitation records from the two recording stations were used to determine the periods of major precipitation. Assuming that the ratios for any one precipitation event are the same as the ratios between the cumulative precipitation at the three stations, an estimate of the major precipitation events in the various sub-periods used in the analysis can be obtained. By using the wind data from the feeder area and the time of each of these major precipitation events, the main wind condition capable of producing an effective transport of the newly fallen material can be obtained. Knowing the wind direction for each of these periods, the effective feeder area for each of the cirques is also known. By repeating this procedure for each of the major precipitation events during each of the various sub-periods in the study, an estimate of the effective feeder area, the time distribution of the precipitation, and the time distribution of the transport are obtained. When these data are combined with the snow survey data of water equivalent for the snow cover in just the effective feeder areas, a water-budget can be performed on each of these smaller areas.

If recording precipitation gages had been used in the feeder area, thus eliminating the need for the transfer of data from remote stations, this procedure might seem reasonable. It does, contain the possibility for the application of considerable judgement to the interpretation of the data primarily with regard to the amount of each precipitation event that was transported from the various effective feeder area.

Comparison of the Two Procedures

The initial test for comparing the procedures was to be based on the periods with the maximum and minimum average wind speeds which were 8 through 31 January and 9 through 22 March, respectively. For the period with the minimum average wind speed there were two periods when the wind was sufficient to cause transport with both following major precipitation events. The wind direction on each of these periods ranged from 245 to 255 degrees which also corresponded to the direction interval in which 93 per cent of all of the winds in excess of 12 mph for the entire 23 day period were contained. The estimated transport over the north cirque obtained from Procedure 1 was 1.77 acre-feet of water while that from Procedure 2 was 1.73 acre-feet. During the period from 8 through 31 January the average hourly wind speed was in excess of the minimum transport velocity more than 70 per cent of the time with 77 per cent of these confined to the direction interval between 240 and 270 degrees. When the two procedures for estimating the transport were applied, values were obtained for the north cirque of 24.95 and 25.50 acre-feet, respectively.

The two procedures were then tried on the period of major variability in wind direction, 23 March through 5 April. Here, the second procedure was greatly influenced by the decision as to how much of the precipitation was transported under the various wind directions following each major precipitation event and thus a wide range in the estimated transport over each of the cirques could be obtained by merely adjusting one of the judgement decisions. The first procedure being free of any judgement terms resulted in only one estimate.

The close agreement between the estimates of the transport resulting from the two procedures under the conditions of relatively constant wind direction suggests that the assumption of uniform transport from the entire potential feeder area, and thus Procedure 1, is a reasonable one at least for this study. When one considers the saltation type of motion for the particles, the wind speed necessary for transport, and the relatively short distance over which the particles travel before leaving the area, the occurrence of "bare spots" and small localized drifting are of minor significance provided that there is a constant source of transportable material at the upstream end of the feeder area which can supply material faster than it is being transported out of the area. Since this condition always existed in the study area, the analysis based on Procedure 1 is believed to be a reasonable one and results in a reasonable estimate of the actual transport over the various cirques in the study area.

With both procedures there is the possibility of interarea transport. This involves the transport of particles first from area 1 to area 2, then from area 2 out of the study area. The results based on the assumption of the departure from the area via route 1 as opposed to its actual route of departure, 2, does introduce a possible error. However, consideration of the possible means by which this transfer can occur indicate that it cannot be of importance in this study. First, if the transfer is the result of eddy movements during the periods of major transport from the entire feeder area, it is reasonable to assume that these are of a random nature and thus the probability of transfer into area 1 is the same as transfer out of area 1 with the net transfer being equal to zero. The second possibility involves the transport from area 1 into area 2 under given wind conditions which result in deposition in sheltered regions of area 2. With a change in wind direction the sheltered regions of area 2 are no longer sheltered and thus transport can occur. This argument is not believed to be applicable to the field conditions encountered. From the orientation of the feeder area, it can be seen (Fig. 3) that in general for this to occur the transport wind must have an easterly component. Not once during the entire study period was a wind encountered that had both the speed necessary for transport as well as a direction that did not have a westerly component. The only significant place where this condition might be important in the study area is the region just to the south of the wind tower when wind directions from the northwest are encountered. Deposition could occur in this region and thus reduce the indicated transport over the south cirque. With a change in the wind direction to the southwest this deposit would be in an unsheltered area and become part of the transport over the north cirque. For this to occur, the wind direction must instantly change through 90 degrees. If the change is slow, the deposit will first be exposed to transport winds which will carry it over the south cirque, and thus not affect the overall results. Since the most rapid change of this magnitude recorded was 13 hours, and further since the individual analysis concerning effective feeder area was based on a change of 15 degrees, such considerations were deemed unnecessary and their error on the indicated results assumed as zero. Here again, the validity of this assumption cannot be tested until such time that sufficient equipment is made available to accurately measure the transport over the ridgeline on each cirque.

APPENDIX B

AVALANCHE TECHNIQUE AND RESULTS

Although each of the four avalanche events can be considered as an individual study, they can NOT be considered as being independent as each blast was affected by all that had occurred in the general cornice area prior to the time of any particular blast. These controlling factors included not only the meteorological factors which influenced the size and the density of the cornice, but also the general condition of the cornice and sidehill as they existed at the end of one avalanche event which corresponded to the beginning of the next study period.

General Procedure and Problems Encountered

The actual technique used on each of the avalanche events was in some way different than what had been tried on the previous events. There were, however, certain procedures, techniques, and general results which were common to all of the avalanche events and will thus be considered first. Except for the special studies on surface directed charges, Dupont Special Gel - 40%, 1-1/8 x 8" dynamite was used throughout. Where reference is made to a given loading in terms of "sticks" it is in reference to this size and type of powder for which each stick weighs approximately 1/2 pound.

Number 6 electric blasting caps were used in all cases with the snowmobile serving as a makeshift blasting machine. This was done by connecting the lead wires to the head light, and switching on the power when detonation was desired. The problems associated with the use of electric blasting caps under the existing field conditions were realized, however, they were preferred by the blasting supervisor. His main arguments being that they were easier to use and more reliable under the existing conditions, and further that the main danger resulting in premature detonation of the cap resulted from blowing snow which occurred only when the general weather conditions were too severe to conduct any extensive field operation.

The cornice deposit in the north cirque was primarily of the "upslope" type and as such, had large deposits upwind of the actual breakoff point. Although the area had been mapped and the anticipated breakoff point marked, the marking was not sufficient along the entire reach to conduct successful controlled avalanching. Since the cornice back of the breakoff point is basically resting on solid ground, it is nearly impossible to avalanche. Any attempts to do so result in not only a waste of time and material but also have a detrimental affect on the overall cornice. If the blast holes are placed back of the natural breakoff point, the blast merely makes a large crater in the deposit without avalanching even the overhang. In addition, numerous fracture lines with surface cracks as much as a foot wide can, and do, occur. These cracks not only make placing additional charges further out on the cornice a very unwise practice, they also provide an interface at which cold air can penetrate deep into the deposit forming ice layers and local areas of increased strength. Of even greater importance is that the existence of these cracks provide avenues along which the shock of subsequent blasts can travel basically unrestricted, thus greatly reducing the effectiveness of any subsequent blast.

These cracks do not fill in as the winter proeeds but rather remain with a thin covering of snow until the melt season begins.

A second problem encountered by not knowing the exact location of the breakoff point is the so called "ice pick condition." Under certain cornice conditions, which are not yet fully understood, the placing of the blast holes in the cornice has the same effect as hitting a block of ice with an ice pick several times in a straight line. Basically the cornice breaks off right through the holes. Such fracture is instantaneous and without warning. Anything located on the cornice beyond the line of holes, such as equipment, personnel, etc., becomes a part of the avalanche material. Both times this condition was encountered, it was during the boring of the seventh or eighth hole in a series. Thus a procedure which involved first boring the holes in a particular series, filling the holes with dynamite, placing the primer on top of the powder, backfilling and tamping the hole use developed.

One additional item concerning the general technique is quite important from a safety standpoint. It was noted above that the primer was placed "on top" of the dynamite. If the primer is placed on the bottom of the hole and the remainder of the dynamite on top, the force of the detenating primer is sufficient to blow out the tamped plug as well as the upper sticks of powder which on occasion ignite at or near the snow surface. This condition is not only extremely hazardous but also results in an ineffective blast with the overall results similar to those mentioned for the holes being too far back of the breakoff point.

Avalanche Number 1

The cornice deposit at the time of the first avalanche, 6 January, was already quite large yet was a natural, undisturbed deposit. The blasting started at the southern end of the large rock outcropping and proceeded first in a northerly direction for about 400 feet. Holes were bored into the cornice to a depth of 10 feet using a standard snow sampling tube and placed approximately 20 feet from the leading edge on a spacing of 8 feet. Each hole was loaded with 9 sticks of powder (including the primer) and 12 holes detonated at one time. These charges were apparently of an ideal size and properly located as nearly 300 feet of cornice was removed. As this large mass of material fell onto the windslab, a much larger mass of material was released. A sketch of the various blast holes and material released is shown in Fig. 27.

The operation was moved north to the end of the remaining cornice deposit and the same series of charges placed, i.e. 12 holes, each containing 9 sticks of dynamite placed 20 feet from the leading edge at a spacing of 8 feet. The results obtained were completely different. About 1/3 of the way along the blasted area the natural ridgeline protrudes a short distance beyond that to the south. As such, some of the holes were placed beyond the natural breakoff point and results similar to those mentioned above were encountered. The blast holes on the northern 1/3 of this section were beyond the breakoff point yet with the cornice attached on each end they merely blewout the bottom of the holes without releasing the overhang. Thus over 2/3 of the section was left in a highly fractured state with large craters in the upper layer of the deposit. The effect of this

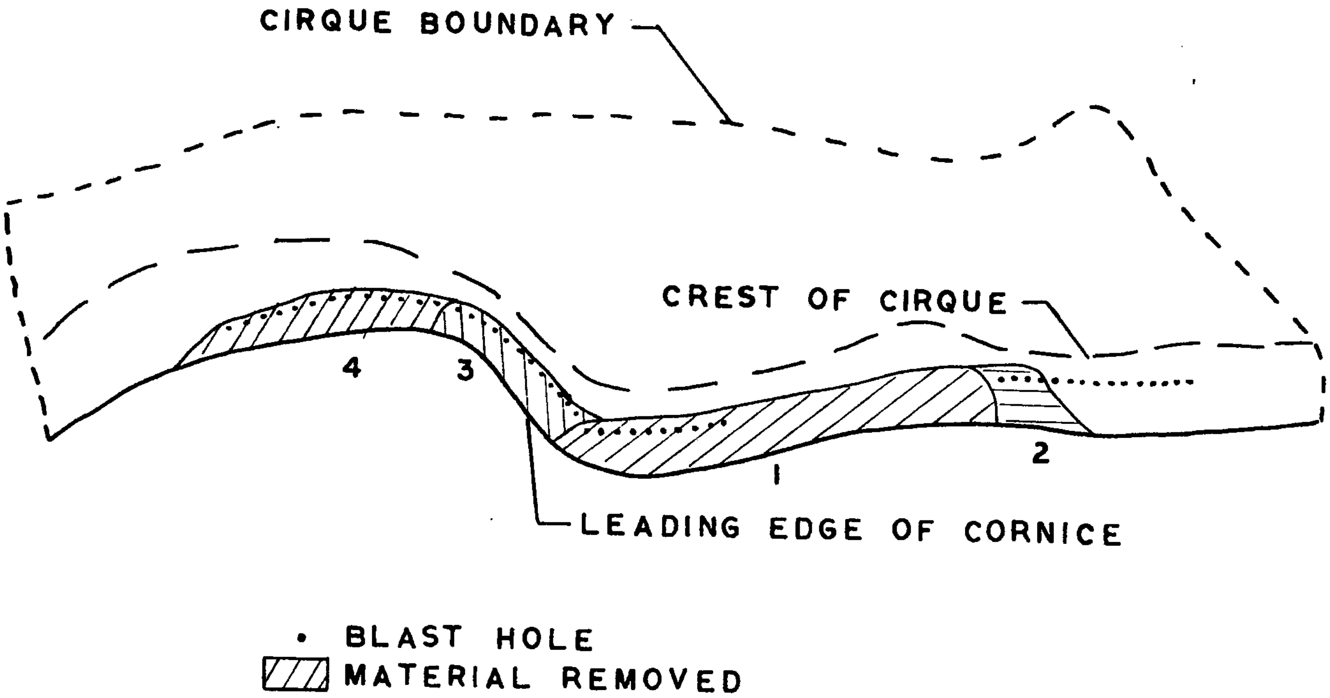

Fig. 27 Blasting pattern used on the first avalanche event.

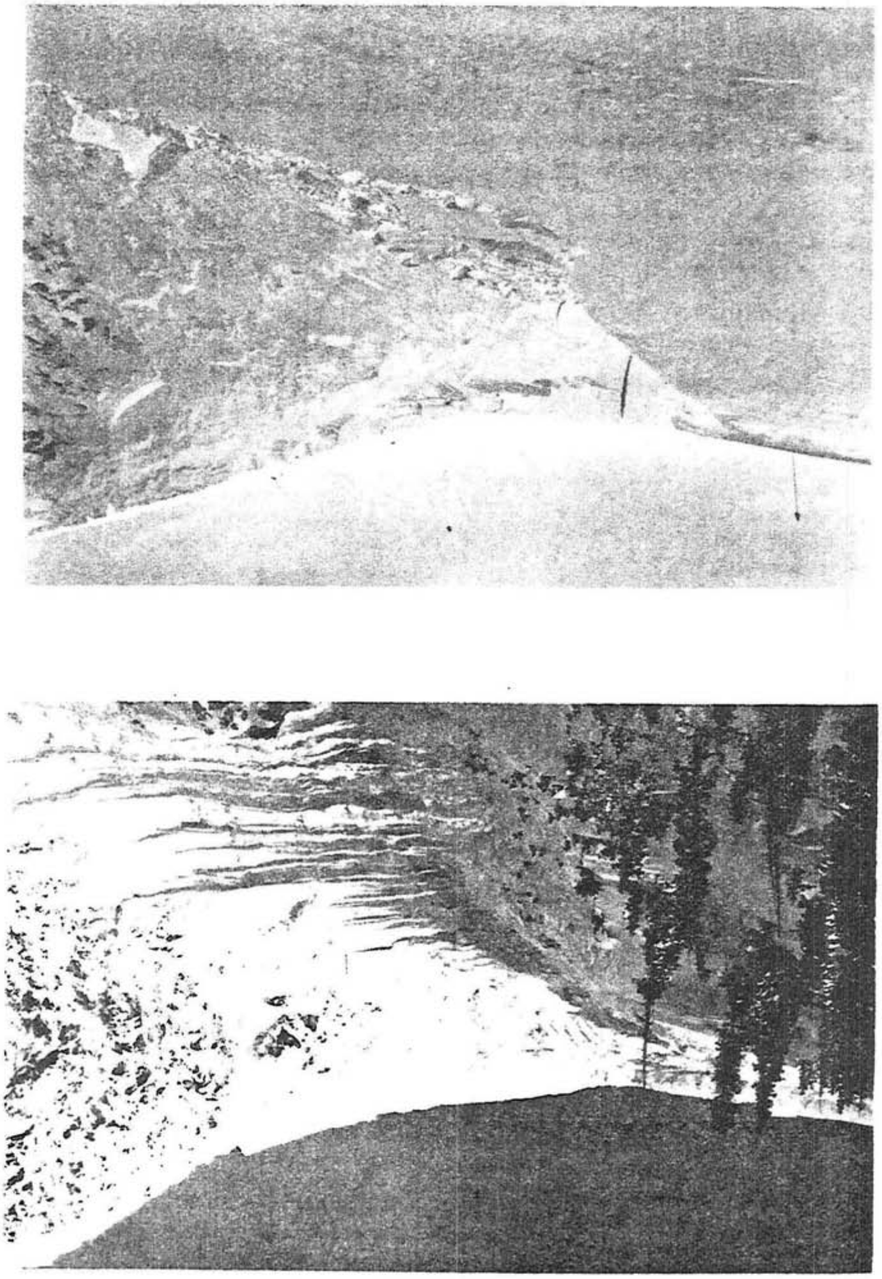

Fig. 28 Photographs of the sidehill following the first avalanche effort.

error was evident for the remainder of the winter and will be discussed later.

In view of the difficulties encountered on the northern end of the cirque, the blasting was moved back to the starting point and continued in a southerly direction around the concave section. Here the same procedure with regards to loading and spacing was used with very good results obtained. One problem, which was not immediately recognized, did occur. After the second blast in this section most of the windslab and sidehill material had been removed leaving the slope in a condition which offered much greater resistance to further sliding than that encountered on the first two blasts. As a result some of the larger pieces of the cornice merely fell over onto the sidehill and came to rest a hundred feet or so down the slope. These pieces, some of which were 30 feet on a side, can be seen in the photographs of Fig. 28. These large blocks within a short time became firmly anchored to the sidehill thus acting as anchors for subsequent windslab deposits. In addition, these blocks appeared to set up secondary eddies in the windslab area as a much more rapid growth of the deposit was observed following their deposition in this region. At first this increased deposition might be viewed as an asset, however, the windslab became so large that it hampered further blasting efforts. It should be noted that the large windslab which subsequently developed was not solely the result of these large blocks yet their influence is believed to have been significant.

Factors Affecting the Second Cornice Development

The period following the first avalanche event was one of extreme wind conditions. During a 94 hour period beginning at 22:00 hour on 9 January the average hourly wind speed never dropped below 30 miles per hour and for 23 of these periods the average velocity was in excess of 40 miles per hour. For this entire period gusts in excess of 85 miles per hour (the maximum value indicated on the recorder) occurred frequently. During the maximum wind period 17 such gusts, in excess of 85 miles per hour, were recorded in one hourly period. The wind direction prior to this period was from 250° and increased to 270° by the end of the period. With the decrease in wind speed a period of variable direction was encountered for almost 18 hours after which the direction again returned to 250° and the average hourly speed increased above the minimum transport velocity where it remained for several days.

During this 94 hour period of intense wind speeds the actual cornice or overhang showed very little change in its overall size. This condition was noted on both the avalanched cornice on the north cirque as well as the undisturbed cornice on the south cirque. The windslab, however, in most locations showed an enormous increase. The windslab in the small concave section on the north cirque increased in thickness from less than 1 foot at the end of the first avalanche to more than 20 feet by the end of this strong wind period. The large blocks of cornice material which had been deposited on the sidehill by the first avalanche were completely covered by the new deposit which at the ridgeline had a horizontal distance from the back to the leading edge of over 70 feet. The average density of the upper 10 feet of this deposit was 59 per cent with a range in densities of from 56 to 64 per cent with no distinguishing variation with depth. This deposit could be considered as total windslab as there was no overhang at the end of this 4 day period.

Large increases in windslab deposits were also noted on the undisturbed deposits on the south cirque. In several sections the region between the cornice and windslab was completely filled in yet the horizontal distance at the ridgeline from the back to the leading edge of the deposit was basically unchanged. This change in the nature of the deposit becomes extremely important in the overall management effort. The basic premis on which the technique was based was one in which the overhang was released and allowed to fall in large pieces upon the windslab at which point the massive impact would trigger the windslab avalanche. Without the overhang the technique was basically useless.

The water content of the deposit on the north cirque was greater on 13 January than it was a week earlier at the time of the first avalanche event when nearly 25,000 cubic yards of material containing an estimated 6.42 acre-feet of water had been removed and relocated in the lower cirque. The cornice deposit should have been removed at this time, however, weather conditions were such that it was impossible to do so until 31 January.

The period between 13 and 31 January was also one of numerous strong wind events with an additional 81 hourly periods with wind speeds in excess of 30 miles per hour and 18 in excess of 40 miles per hour. During the periods of moderate transport from the feeder area a relatively small overhang developed with the windslab becoming even larger.

Avalanche Number 2

Biased by the results obtained on the first avalanche, the same procedure was tried on the second. The first blast which again extended from the southern edge of the large rock outcropping in a northerly direction for approximately 100 feet released several large pieces of cornice material yet basically none of the windslab. The motion pictures which were taken at each of the avalanche events revealed that one piece of the cornice material released by the first blast merely bounced down the slope. This piece which was estimated at approximately 20 feet on a side and an estimated weight of 120 tons bounced off the windslab four times traveling more than 100 feet down the slope on each bounce yet never triggering a sidehill avalanche. The block merely came to rest in the deposit area some 500 feet lower in elevation generally unchanged by the trip down the slope.

The second blast yielded the same results. The region of the third blast was that where difficulty had been encountered on the first event and thus the row of charges was moved to within 15 feet of the leading edge. On more than half of the bore holes in this region, old powder smoke identifiable by its distinct odor and numerous subsurface voids were encountered. Whenever one of these voids was encountered, the bore hole was moved in order that the charge could be placed in solid material. The overall results, however, was unsuccessful in that only more surface craters approximately 6 feet in diameter and numerous fracture lines occurred without releasing the overhang.

The operation was then moved to the concave section just to the south of the first blast. On the fourth blast reasonable results were obtained in terms of cornice removal. The fifth and final blasts yielded results similar to those of the third. Although a small portion of the overhang was removed, the supporting windslab was so close to the leading edge of the cornice that a ledge was formed after the blasting. This ledge which was located approximately 10 feet below the top of the deposit had as a leading edge the relatively unaffected windslab.

The field experience encountered on the second avalanche event indicated among other things that the windslab was the major deterent to a successful blast. It was therefore decided to try an alternate blasting procedure aimed at first removing a part of the windslab before an attempt was made on the cornice deposit. Again hampered by unfavorable weather conditions, the attempt was delayed until 9 March.

Avalanche Number 3

The first item tried was the use of surface directed charges placed on the windslab in a location which would correspond to the natural fracture line of the deposit. This was done by placing three two pound Boulder Busters* in a plastic bag and lowering the bag by means of a small rope to the desired location. The charge in each of these bags had a shock power equivalent to 15 pounds of 65 per cent dynamite. This product which has shown to be quite successful in the

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*These are a surface directed charge manufactured by Kinetics Internation Corporation of Dallas, Texas.

control of avalanche deposits as encountered in ski hill operations had little effect on the massive windslab with the general effect limited to a dark powder stain on the surface. On one such blast the lead wire to the electric cap became disconnected during the placement procedure. Since the overhanging cornice prevented the retrieval of the charge, a second bag was lowered and placed in contact with the first. When the second bag was ignited the first was also detonated. At the same time a third bag located further to the south was also detonated. The combined effect of these three charges was an extremely loud blast which caused minor effect to the windslab. The area affected is shown in Fig. 28. Here it is noted that on the far left of the photograph a small portion of the windslab was removed with the distinct layering nature of the deposit clearly shown. The main effect, however, was the large piece of cornice material dislodged by the shock of the combined blast. The average dimensions of this piece were 20 by 20 by 100 feet with a weight in excess of 600 tons. Although the block appears to be in a somewhat unstable position, it was actually resting on the windslab and highly resistent to further movement. Since it did offer a deterent to further blasting, it was removed separately by placing three charges of 50 sticks of dynamite in holes dug under the back edge of the contact surface. Access to this location was obtained by climbing down the large crack seen at the back of the piece. During the movement of this material down the surface of the windslab, no noticeable increase in material was seen and the surface of the windslab after the motion had ceased was basically unchanged.

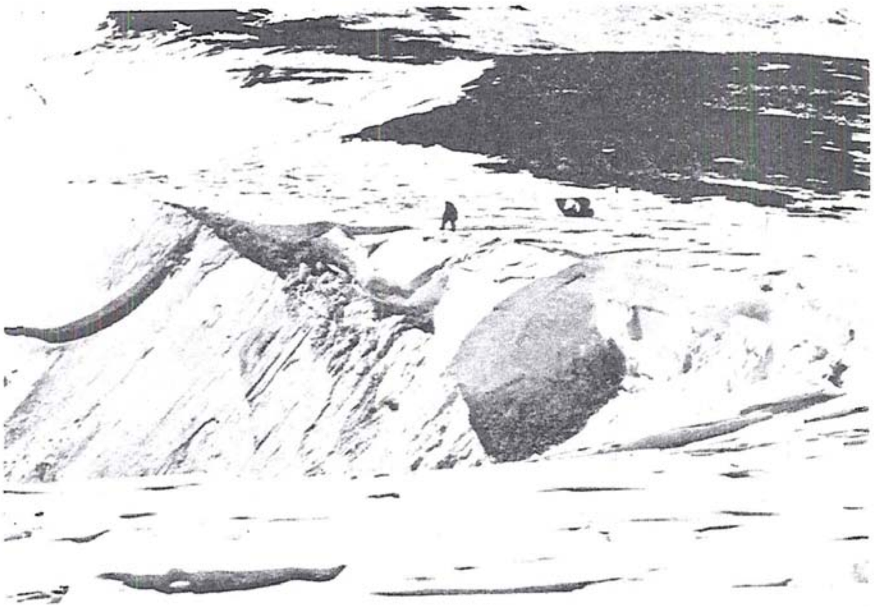

Fig. 29 Photograph showing the effect of Boulder Busters lowered over the leading edge of the cornice onto the windslab deposit. Note the layering of the windslab shown in the upper left of the photograph.

The remainder of the blasting followed the same pattern as the previous events with the major difference being the size and location of the charge. Instead of using the 1-1/2 inch diameter snow sampling tube, a modified post hole digger with 16 foot handles was used for digging the holes. Each hole was then loaded with 50 sticks of dynamite, backfilled, and tamped. With the previous hole arrangement the dynamite was stacked one on top of the other over a considerable distance. With the larger hole a much stronger charge could be placed at a lower depth in a more concentrated location. The same blast pattern was used here as on the previous attempts with similar results obtained on the northern section of the deposit. Here again old powder smoke was noted on many of the holes further indicating that these cracks and voids in the cornice do not fill in but rather stay as an integral part of the deposit. On the remaining parts of the deposit, moderate to good removal was obtained at least in terms of absolute quantities. However, when one considers the material moved in terms of unit volume moved per pound of explosive the results were extremely poor being approximately 1/5 of that obtained on the first avalanche.

The main item realized from the third avalanche event was that the charges were not placed at a great enough depth to effectively blow out the lower portion of the cornice-windslab deposit. By having the charges too high, the upper portion was blown off leaving a ledge which supported much of the fractured material. Figure 30 shows the results obtained by improper placement resulting from either the hole being too high or too far back from the leading edge while Fig. 30 represents the desired condition.

In hopes of obtaining a better placement of the charges a power auger with four 4-foot long sections having a diameter of 3-1/2 inches was tried. It was found that an excellent hole could be obtained with this arrangement and that by using a straight pipe section in addition to the four auger sections an even deeper hole could be obtained. There was, however, one major difficulty with this arrangement. When the boring of the hole was complete, the four auger sections were all attached into one unit which weighed approximately 110 pounds. Once the drilling had stopped, the auger had to be removed immediately or it would freeze in the hole and become impossible to remove. Even without the freezing, the removal of this auger was extremely burdensome requiring at least two and preferably three men for the operation.

Avalanche Number 4

The power auger was used to drill all of the holes on the fourth avalanche. The holes were either drilled to the ground surface or the maximum depth of the auger which was either 16 or 20 feet depending on whether or not the additional straight section could be used. The same spacing of approximately 8 feet between holes was used in the same general pattern as employed on the previous events. Each hole was again loaded with 50 sticks of dynamite with 12 to 15 holes being detonated at one time. With the deeper holes and initial ripening of the deposit brought about by a period of warmer weather, much better results were obtained.

Summary of the Results

The material presented in the above discussion has been summarized in Table 13. When these results are combined with the results obtained

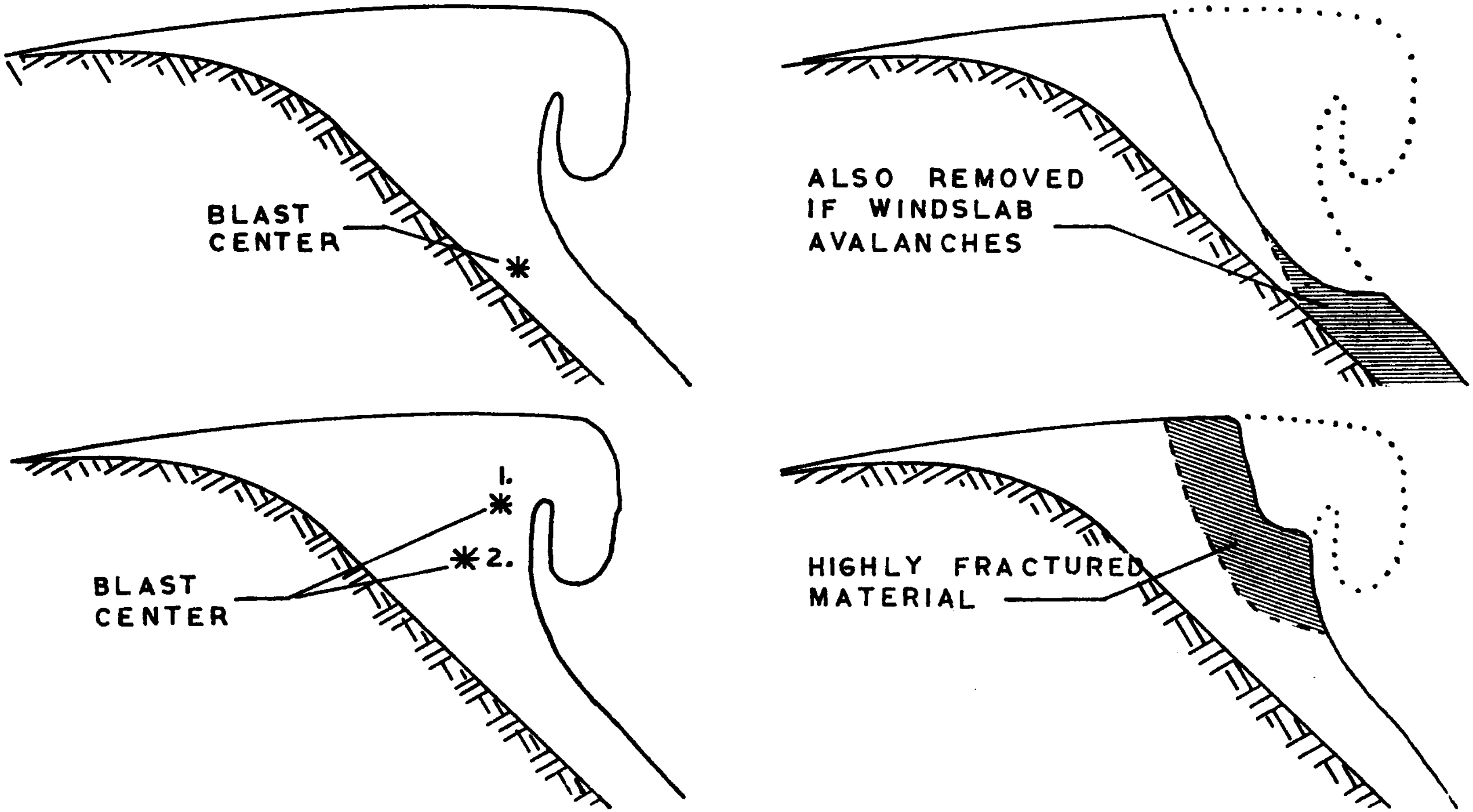

Fig. 30 Schematic diagram showing the results obtained from (A) a properly placed charge, and (B) an improperly placed charge. 1 is too high and 2 is too far back.

TABLE 13

Summary of Blasting Effort

Avalanche Number	1	2	3	4
Volume removed in ac.-ft. of water	6.42	1.37	3.10	5.31
Pounds of dynamite	300	300	600 plus 24-2# BB	1350
Relative effect on windslab	good removal	basically none	rock face only	rock face little elsewhere
Boring procedure and evaluation	1 1/2" dia. snow sample tube good	1 1/2" dia. snow sample tube satisfactory	6" dia. post hole digger very slow	3 1/2" dia. power auger burdensome
Max. depth of holes	10 ft.	10 ft.	15 ft.	16 ft. ave. 20 few
Ave. size of charge in sticks/hole	9	9	15	25
Degree of blowout	minor	minor	every hole 50-100' high	every hole 50' high
Efficiency in ac.-ft./100 lbs. dynamite	2.14	0.46	0.52	0.39

on previous studies in the same general area* several general statements can be made concerning the avalanching of large cornice deposits.

1. A fresh, undisturbed cornice is much easier to remove than one that had previously been avalanched.
2. An unsuccessful attempt to remove the cornice leaves the deposit in such a condition that further attempts are much more difficult. Furthermore, a slight saving which might result from underloading a series of blast holes may require from 5 to 10 times the initial investment if the removal is unsuccessful.
3. A second avalanche in an area will require a minimum of twice the shock power needed to avalanche the undisturbed cornice.
4. It is desirable to have the charge as close to the natural slope as possible.
5. Although it is desirable to have pieces of cornice material fall onto the windslab to help trigger a sidehill avalanche, the lodging of these pieces on the upper slope aids in the formation of an increased windslab which hampers further removal efforts.
6. For an effective removal program, the cornice-windslab deposit should be kept to as small a size as possible with avalanching as close as weekly intervals when necessary.

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*Some preliminary work on avalanching had been done by other members of the CSU research team several years before this study but no publication of the findings was made.

APPENDIX C

PORTION OF ALTA AVALANCE STUDY CENTER

MISCELLANEOUS REPORT NO. 14

THE NATURE AND CONTROL OF SNOW CORNICES ON THE BRIDGER RANGE SOUTHWESTERN MONTANA

by

John Montagne, et. al.

INTRODUCTION

Prevailing westerly winds create large snow cornices along the lee crest of the Bridger Range in Southwestern Montana. Studies during the winters of 1965-68 revealed some of the mechanics of cornice accumulation and deformation and showed that cornices may be controlled by wind deflecting structures. The study site averages 8500 ft. (2590 m.) A.S.L. and extends a linear distance of one half mile (0.8km.) at the head of the Maynard Creek watershed. Prevailing winds are from the west, or approximately perpendicular to the Bridger ridgeline. Maximum wind speeds occasionally exceed 100 mph (44.7 mps).

Since a high proportion of naturally triggered avalanches in many recreation areas are caused by cornice collapse, prevention or control of these features is of importance where recreational safety is of primary importance.

To a large extent, this paper is an embellishment of the excellent pioneer writings of Wellzenbach (1930), and Seligman (1936), and the unwritten ideas of that master mountaineer, Andre Roch.

DEFINITION

For purposes of clarity, a cornice (German "Wachte") is defined as a projection of snow formed by wind deposition to the lee of a ridgeline or slope inflection. A typical composite cornice is illustrated in Fig. 1.

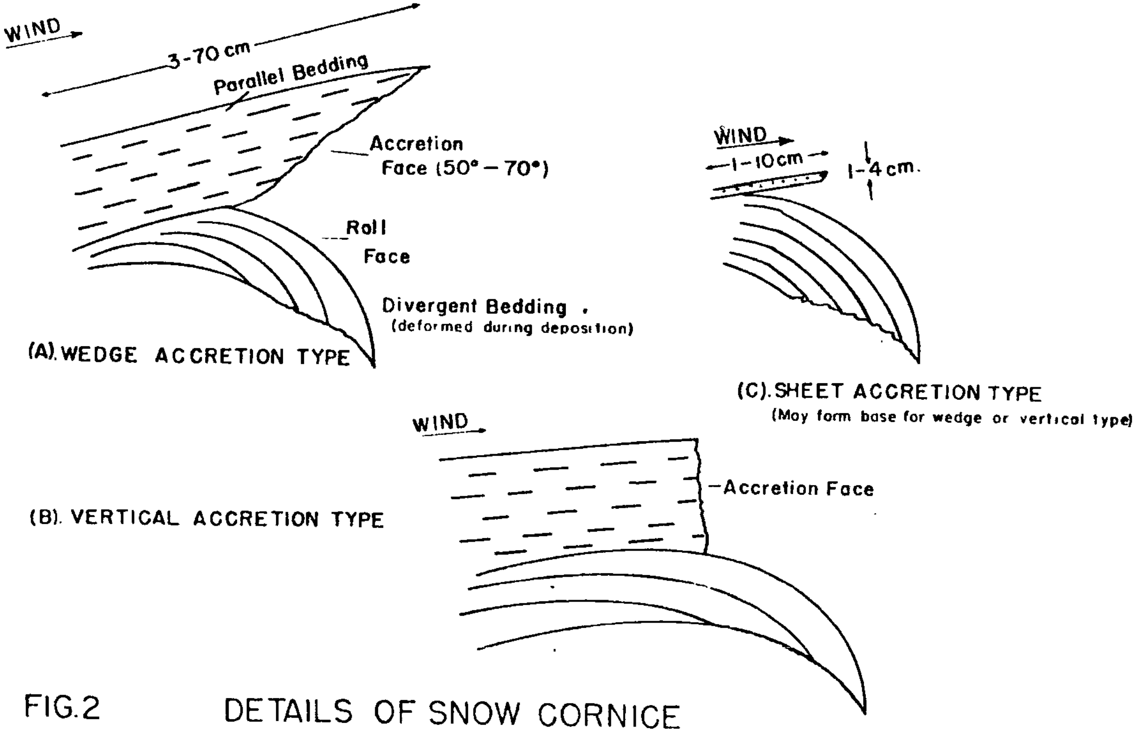
STORED WATER

The declivity of lee slopes controls the size of cornices developed upon them, hence the amount of water that is available from cornice snow. The lee slopes on the Bridger Range average about 35° in inclination. On such slopes, maximum vertical thicknesses of cornices in late winter measure about 10 m. These cornices correspondingly extend upward and outward from the ridgeline as much as 15 m. (Fig. 3a). If the slopes are steeper than 35°, the horizontal component of development is limited because there is less support along the lee slope line.

On 35° lee slopes, measurements made April 2, 1967, indicate that approximately 54 acre feet (67,688 m^3) of water was contained within the cornice masses along the 2.5 km crestline above the Maynard Creek watershed (Fig. 6). This amounted to about one percent of the total equivalent water estimated to have been stored in the watershed at that time.

CORNICE MECHANICS

Wedge and Sheet Cornice Growth. Several processes may contribute to cornice growth. The most common type of growth is caused by the downwind accretion of snow particles in progressive outward and upward extending layers. The process forms a wedge shaped mass along the leading edge. As a variation to the wedge type growth, under conditions of particularly effective grain to grain adhesion and copious supply of stellar flakes, a horizontal sheet of snow only a few cm. thick may extend as much as 10 cm. into space (Fig. 2C). These sheets or wedges



(A). WEDGE ACCRETION TYPE

(B). VERTICAL ACCRETION TYPE

(C). SHEET ACCRETION TYPE
(May form base for wedge or vertical type)

FIG.2 DETAILS OF SNOW CORNICE ACCRETION ZONES

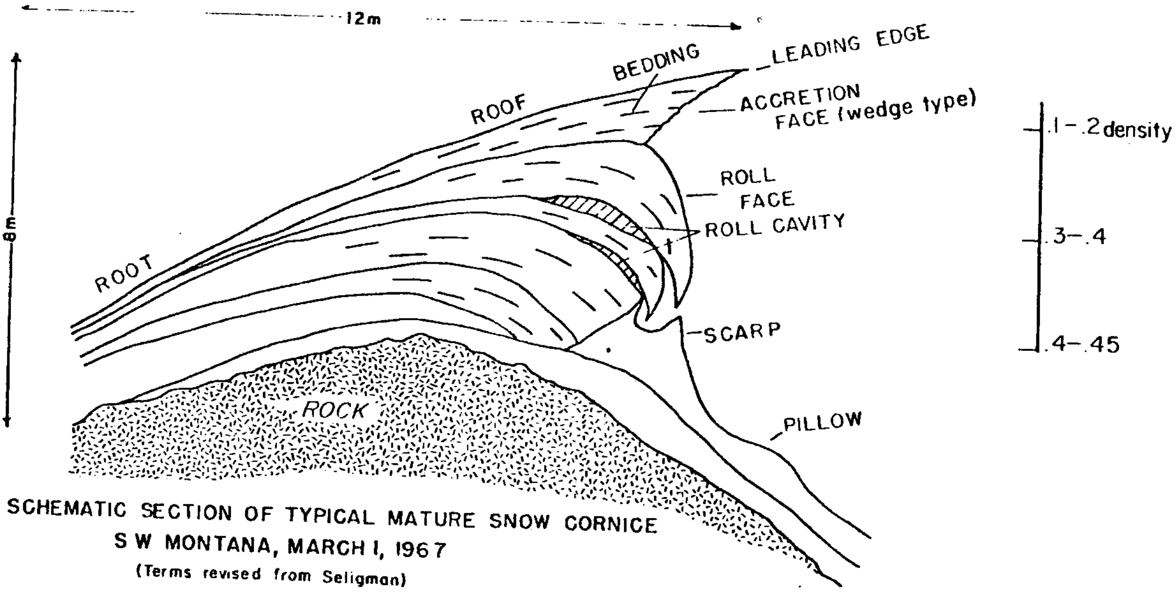


FIG. 1 SCHEMATIC SECTION OF TYPICAL MATURE SNOW CORNICE
S W MONTANA, MARCH 1, 1967
(Terms revised from Seligman)

may eventually collapse or sluff off their own weight, may stiffen to form the base on which succeeding layers build, or may curl downward plastically under the influence of gravity. In the wedge type, the accretion face (Fig. 1) has an underslope that slants inward toward the main cornice mass at an initial angle of about 55°. When the wedge is deformed, as it usually is, the angle of the accretion face changes, of course.

When conditions are not favorable for wedge accretion, the cornice roof can often build upwards but without horizontal extension. In this case, the accretion face (Fig. 2B) remains approximately vertical.

Clinging Mechanism. Photos indicate wedge accretion (Fig. 2A) to be most commonly brought about by the mechanical clinging of either rimed or unrimed new stellar snow flakes under a wide range of temperature, wind, and humidity. The crystalline appendages can adhere mechanically to one another along the leading edge until sintering takes place and hardens the mass. Seligman (1936) believed this was the only mechanism which could account for horizontal growth of cornices.

Granular Cornice Growth. Although wedge accretion most commonly forms from stellar snow, macro photographs taken of granular snow during cornice growth suggest that this form of snow can also cause wedge accretion. The latter type of growth has been observed only during conditions of high relative humidity, slightly below freezing temperatures, and moderate surface wind speeds of from 15 to 35 mph (7 - 15 m./sec.). Although very difficult to measure quantitatively, rounded saltating grains apparently adhere and sinter nearly instantaneously at the tip of the leading edge. The edge is thus extended particle by particle outward and upward. The mechanism for this very rapid sintering process is unclear at present.

Discussion of Adhesion Causes. It is possible that riming and electrostatic effects are important in grain adhesion prior to sintering. However, it should be noted that wedge growth by accretion of granular particles has been observed both on clear days and on days when riming was occuring.

Other possible mechanisms to explain such adhesion and rapid sintering are now under study. These include the measurement of possible temperature drop due to wind diffusion near the cornice edge and the inspection of grains for free water coating.

Densities in the forming cornice wedge may range from 0.1 $g/cm.^3$ for the clinging stellar snow types to 0.25 $g/cm.^3$ for the sintered granular type.

If humidity, temperature, and snow conditions are favorable, cornices can build under relatively low wind speeds (about 16 mph or 7 mps). Naturally, a source for the snow supplied to the leading edge is a prerequisite. Often the only such source is the root of the cornice itself, which tends to scour as the leading edge extends. Ordinarily, winds above 60 mph (27 mps) will scour the entire cornice surface and abruptly reduce its height.

CORNICE DEFORMATION

Several types of deformation may take place within the cornice mass. Gravity is primarily responsible in all cases. Qualitatively, it has been observed that deformation of the growing edge is accelerated under near freezing conditions because of the increased plasticity of snow.

Roll Cavity. A critical aspect of deformation is the downward folding ("involution" of Seligman 1936) of the accretion wedge to form a curved tongue which usually encloses an air space beneath and behind it (Fig. 1). We have named this air space the "roll cavity". Folding may well exceed 90° and is brought about by intergranular adjustment. The weakness zone thus created may be several feet in both height and width, depending upon the geometry of the original wedge and the amount of folding which has taken place. Since the roll cavity tends to persist, at least in compressed form, it remains a weakness zone within the cornice mass that tends to localize future fractures. These zones can be exploited when dynamiting cornices for control purposes. Using time-lapse photography, we were able to demonstrate that some deformation is contemporaneous with cornice growth. When this happens, the bedding layers in the accretion wedge tend to diverge toward the upper and outer edge. Slightly below freezing temperatures seem to be prerequisite for such contemporaneous deformation to occur.

Bedding. Under relatively cold conditions, contemporaneous deformation is minimal and divergent bedding does not form during accretion. Thus, by analyzing the nature of the bedding, it is possible to estimate the temperature conditions under which the cornice wedge formed.

Welzenbach and Paulke (1928) originally had observed that involution of the growth wedge could be contemporaneous with deposition, as described above. They suggested that the amount and rate of deformation depended upon the infiltration of water in the cornice. To date, no relation between rate of deformation and infiltration of water has been noted on Bridger Ridge. It is hoped that experiments with dyes may indicate the true nature of intergranular movement involved with cornice deformation.

Creep and Glide. The entire cornice mass creeps and/or glides continuously. Such movement is well known for snow in general (see, for instance, in der Gand and Zupancic, 1965). As creep or glide progresses, tension fractures tend to develop between the cornice mass and ridgeline bedrock. During the winter of 1967-68 at Bridger Ridge, the cornice root moved away from the ridgeline leaving a tension fracture 1 m. in width near the surface. Bits of bedrock embedded in the icy wall of the cornice mass proved that the wall was once in contact with the rock.

In order to determine the nature of deformation within the main cornice mass, vertical rods emplaced in the cornice roof behind the leading edge were observed over a period of several weeks. As in typical snow creep, the rods were tilted as much as 30° from the vertical (downhill) within 9 days. Similarly, strata marked with spray paint and originally having 14° westward inclinations, were tilted 20° eastward after 9 days of observation. Thus, the entire cornice mass tends to roll downward in time. It should be emphasized that this type of deformation takes place within the solid part of the cornice and is independent of the more rapid deformation of the unsupported accretionary wedge described above.

WIND DATA

Anemometers were placed parallel to the wind direction and 35 cm. above the snow surface on a cornice roof that was slightly convex upward. It was found that the wind speed was reduced several percent toward the leading edge of the cornice. This phenomenon had previously been noted by Seligman (1936) and probably results from the divergence of air moving over the convex surface. Parenthetically, it may be stated that a convex cornice roof is usually the result of deformation.

An abrupt reduction in wind speed takes place below and to the lee of the leading edge. Here, in spite of high winds above the cornice roof, significant vertical vortices of the type postulated by Welzenbach (1930) do not develop. This conclusion was reached after observing that soap bubbles released in the space beneath the leading edge of the cornice exhibited only a slow drifting motion when high winds were blowing above. Likewise, overshot snow sifting through this zone tends to fall to the base of the cornice face. Snow does not significantly plaster to the face unless blown by eddy currents that flow through gaps in the cornices.

"Suction Cornices". The idea of a "suction cornice" originated with Welzenbach (1930). He postulated that the vertical vortices mentioned above could hollow out the space beneath the accretionary wedge and could help extend the leading edge by deposition from below. This idea was refuted by Seligman (1936) who also concluded that the vertical vortices were not strong enough to significantly influence cornice growth. Nevertheless, Seligman applied the term "suction cornice" when discussing the building of cornices from stellar flakes that cling together along the leading edge below the air stream.

"Pressure Cornice". Seligman also retained Welzenbach's term, "pressure cornice" to describe the wind-packed snow that is built into the air stream along the cornice roof, there to be hardened by sintering. Because neither "suction" nor "pressure" accurately suggest the nature of cornice accretion, it seems advisable to abandon these terms in future usage.

Other Terms. We recommend retaining the term, "scarp" for the steepfronted drift that builds along the lower cornice face by the fall of oversnow snow (Fig. 1) and we also recommend retaining the term, "snow cushion" or "pillow" for the low drift that connects the scarp with the undisturbed snow of the lee slope.