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THE FEASIBILITY OF ENHANCING STREAMFLOW IN THE SEVIER RIVER BASIN OF UTAH BY SEEDING WINTER MOUNTAIN CLOUDS

by

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EXECUTIVE SUMMARY

The main goal of this feasibility study was to examine the suitability of the Sevier River Basin for application of winter cloud seeding intended to enhance the high altitude snowpack. In large measure this meant examination of the meteorological conditions during storms with particular emphasis on the availability of supercooled (below 0 °C) liquid cloud water. Additional goals were to develop an experimental design to validate the effects of winter cloud seeding in the basin, and to estimate probable benefit-cost ratios for an operational seeding program.

A brief discussion is given of the fundamentals of winter mountain clouds and cloud seeding. Basically, for seeding to be effective, clouds must exist that are at least partially composed of tiny SLW (supercooled liquid water) droplets that are not naturally converted to snowflakes. Seeding involves conversion of some of the cloud droplets to ice crystals that can grow to snowflake sizes and settle to the surface. Ice crystals rapidly grow in a supercooled liquid droplet environment because of the difference in saturation vapor pressure over water and over ice. Forced uplift of moist air over a mountain barrier can produce abundant SLW over the windward slope and crestline but the SLW normally evaporates to the lee of the mountain as the air descends and warms. Thus, cloud seeding is a "race" between formation of ice crystals and their growth and fallout to the surface before the cloud droplets descend and evaporate downwind of the barrier.

The most common seeding agent is silver iodide (AgI) which has a crystalline structure similar to ice. It can be released from the ground to produce significant concentrations of ice crystals in liquid clouds colder than about −8 °C. Methods of abruptly chilling the air; for example, by the use of dry ice or by the expansion of propane or other gases, can be used to create ice crystals in liquid clouds colder than 0 °C.

Statistical evidence is reviewed from both operational seeding intended to increase snowfall, and experimental seeding intended to increase knowledge. The statistical evidence from Utah is inconclusive but suggests seasonal snowfall increases of about 10 percent may have been achieved. Similar suggestions have resulted from some other projects in the West but scientific evidence is still lacking.

A considerable body of physical evidence has been collected in Utah and some neighboring states in recent years concerning the availability of SLW, a necessary ingredient for cloud seeding to be effective (it is recognized that SLW availability does not in itself guarantee seeding potential). Review of this evidence shows a considerable amount of SLW passes over mountain barriers during the course of each winter without being converted to snowfall. The amount of excess SLW is roughly of the same magnitude as the annual streamflow from the mountain watersheds that have been studied in Arizona and Utah. Thus, the "raw material" needed for cloud seeding exists in abundance. Most of the seasonal flux of SLW is concentrated in a few large storms that produce significant snowfall during their more efficient stages. The challenge is to optimize the conversion of excess SLW into snowfall during inefficient storm stages.

The major uncertainty with winter orographic cloud seeding concerns delivery of appropriate concentrations of seeding material to the proper cloud regions. Many winter orographic programs use AgI ground generators but limited documentation exists concerning the T&D (transport and dispersion) of the AgI into the clouds. Does the AgI reach the desired cloud region when and where SLW is present and, if so, are AgI concentrations adequate to create significant numbers of ice crystals? There is considerable evidence to suggest that valley-released AgI often is trapped in a shallow layer due to the stability of the lower atmosphere. On the other hand, frontal passages may transport this seeding material into the clouds. Moreover, embedded convection was shown to transport valley-released AgI well up into the mountain clouds during the early 1991 field program in central Utah. A number of studies have shown that high

altitude generators consistently produce AgI plumes over mountainous terrain within the SLW zone. However, additional T&D investigations are needed to enable improved delivery of adequate concentrations of ice nuclei to SLW cloud regions.

A large percentage of winter storms are too warm for seeding with ground-released AgI which has limited effectiveness at temperatures above about −8 °C. Even the expensive option of aircraft AgI seeding might not be effective in many of these cases because the SLW is concentrated near the ground where the temperature may be too warm for significant ice crystal formation. Options such as propane seeding should be explored for warm storms so the effectiveness of seeding may be optimized.

Storms typically go through a series of stages in their passage over a mountain region. Studies of these storm stages are reviewed with emphasis on the availability of SLW and the T&D of ground-released AgI. It is shown that seedability often varies considerably during a storm passage and also from storm to storm.

Long-term precipitation and temperature records are considered from a high altitude weather station in the Sevier Basin. These provide estimates of typical storm frequencies and precipitation amounts and how these range from season to season. Precipitation days, which can be considered a proxy for days in which seeding might be conducted, varied from 30 days during dry winters to 60 days during wet winters. Although the number of precipitation days are variable, even dry winters appear to have enough for frequent seeding operations. Temperature data indicated nearly 80 percent of the days with snowfall were −6 °C or colder at the weather station.

Review of the available evidence indicates several uncertainties about the effectiveness of cloud seeding as currently practiced in Utah and the West in general. A number of options are available to deal with these uncertainties as briefly discussed. The option recommended is believed to offer the most rapid means of removing uncertainties associated with the Utah operational cloud seeding program, but it is a relatively expensive option. The recommended approach is to conduct a demonstration program in the Sevier River Drainage to validate winter orographic cloud seeding. Accordingly, design considerations are reviewed and the best experimental area is selected for the basin. A two-stage program is proposed that would emphasize cause-and-effect physical experiments over a limited area during the first phase. The second phase would consist of a statistical/physical experiment to confirm the multiwinter increases that seeding could produce over a large area.

Preliminary benefit-cost estimates are given based on an assumed increase in seasonal snowpack with subsequent runoff calculated by a snow accumulation and ablation model. An economic analysis by the Utah Division of Water Resources provided the value of the calculated additional water. Two costs of operational seeding were used. The first reflects the costs of the Utah operational seeding program as currently conducted, using widely spaced valley generators. The second estimate reflects the additional costs of using closely spaced, high output generators well up the windward slopes to improve targeting. The results indicate benefit-cost ratios from about 3:1 to more than 10:1, depending upon the assumptions made. If winter cloud seeding can provide mountain snowfall increases approaching or exceeding 10 percent, the technology should have good economic justification.

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GLOSSARY

AgI . . . . . silver iodide
DOT . . . . . Department of Transportation
DWR . . . . . Department of Water Resources
IPC . . . . . ice particle concentration
m.s.l. . . . . mean sea level
NOAA . . . . . National Oceanic and Atmospheric Administration
NWS . . . . . National Weather Service
SLW . . . . . supercooled liquid water
T&D . . . . . transport and dispersion

1. INTRODUCTION

The Bureau of Reclamation (Reclamation) and the Utah DWR (Division of Water Resources) are mutually interested in determining the feasibility of enhancing the winter snowpack and subsequent runoff in Utah's Sevier River Basin shown on figure 1-1. Reclamation investigated the potential of developing a technically sound and validated snowpack enhancement program for the Sevier River Drainage. The technology of weather modification, commonly called cloud seeding, was to be considered as the means of snowpack augmentation. Much of the streamflow in the Sevier River is due to the spring and early summer melting of the mountain snowpack in the basin.

The objectives of this investigation were (1) to determine the meteorological feasibility of increasing the water yield of the Sevier River Basin through the application of state-of-the-art winter cloud seeding to mountain clouds, (2) to develop an experimental design to scientifically validate the effects of cloud seeding in the basin, and (3) to provide reasonable estimates of the magnitude of the precipitation and resulting streamflow increases that might be expected from operational seeding, and the benefit/cost ratio of such application.

Investigations of winter snowpack enhancement by cloud seeding in Utah began in the late 1960's. Early support of this work was provided to Utah State University by Reclamation's Project Skywater. Detailed analyses of experimental seeding from the winters of 1969-70 through 1975-76 were reported by Hill (1979).

Since 1981 a research program largely sponsored by NOAA (National Oceanic and Atmospheric Administration) has investigated the effectiveness of the Utah operational seeding program (Reinking, 1985). This Utah/NOAA Atmospheric Modification Program has investigated the physical processes that occur in both seeded and nonseeded winter storms passing over the Tushar Mountains of south central Utah. A series of comprehensive Final Reports has documented these studies. These reports and associated publications in the scientific literature, reviewed in section 3, have provided information that has substantially contributed to this feasibility study.

In addition to reviewing the results of past research efforts in Utah, and similar studies from nearby states in the Rocky Mountain region, this report examined precipitation data from Cedar Breaks, UT. Blowhard Mountain radar, a site atop Cedar Breaks, provided high altitude data in the Sevier River Drainage with a reasonably long-term record. Observations from this site are assumed to approximate the snowfall climatology for the higher elevations in the drainage which provide much of the streamflow.

Hydrological modelling studies have been provided by the NWS (National Weather Service) River Forecast center in Salt Lake City, using estimated increases in precipitation expected from cloud seeding. From the NWS model results, a determination of the benefits of cloud seeding was made by DWR personnel. These estimates, along with probable costs of conducting an operational program, provided information for a preliminary benefit-cost analysis. However, a number of uncertainties exist in making the benefit-cost estimates that can only be clarified by more definitive physical and statistical studies than conducted to date.

The review in section 3 revealed several uncertainties concerning the effectiveness of winter cloud seeding. Consequently, considerable attention is given to designing a weather modification demonstration program for the Sevier River Drainage. These uncertainties are not unique to the Sevier Drainage or even to the State of Utah, but many of them should be answered for the intermountain West in general in order to place the technology of winter cloud seeding on a firmer scientific footing.

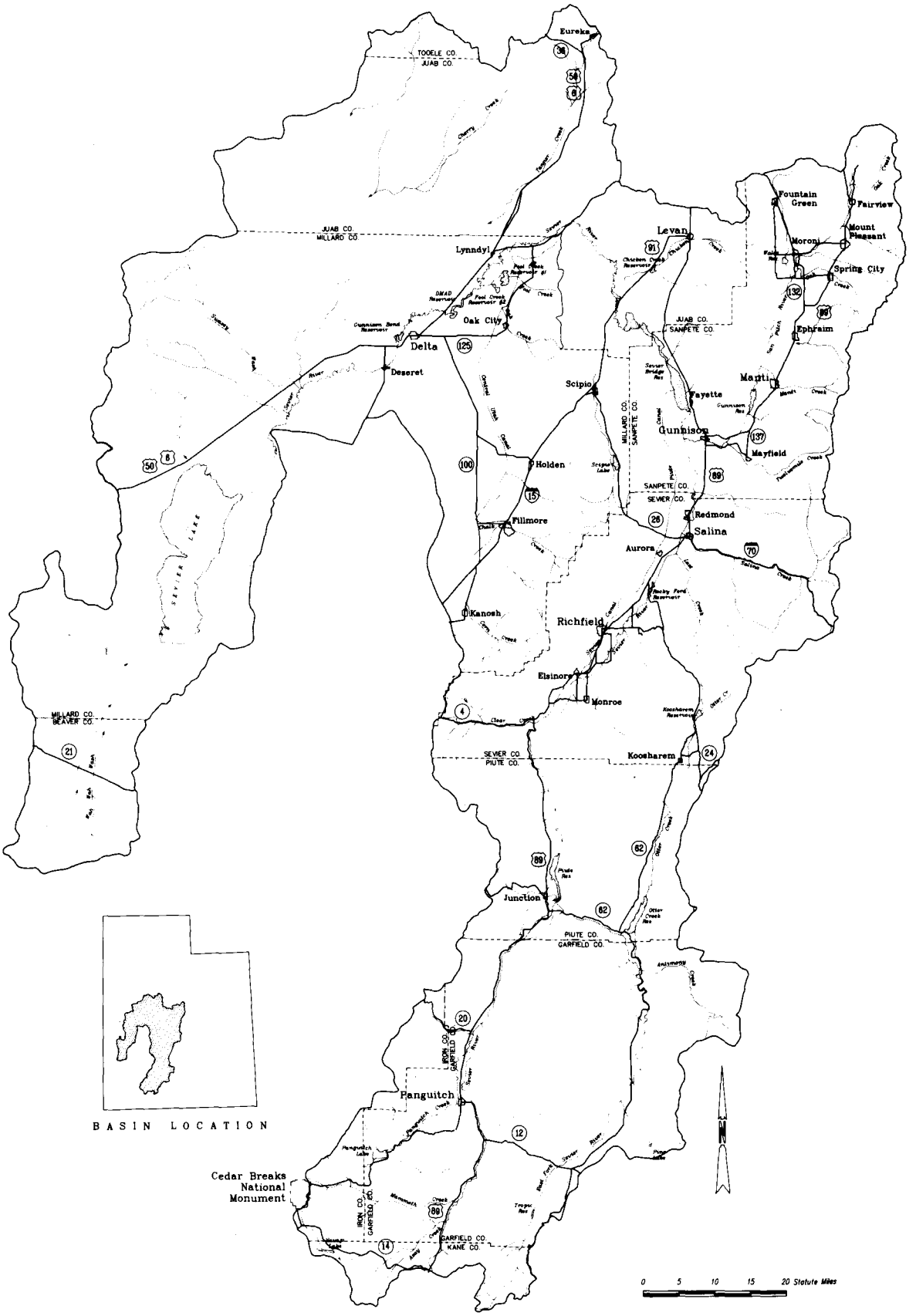

Figure 1-1. - Map of the Sevier River Basin showing streams and county boundaries.

2. FUNDAMENTALS OF SEEDING WINTER CLOUDS OVER MOUNTAINS

An understanding of the fundamentals of winter cloud seeding over mountainous terrain is necessary to much of the discussion in this report. Accordingly, a brief description is given in this section.

2.1 Winter Orographic Clouds

Winter clouds over mountains are often referred to as "orographic clouds" as they are wholly or partially produced by the uplift of moist air which can occur when airflow is forced over rising topography. The term orographic cloud in a strict sense refers to local clouds whose form is determined by the effects of terrain on the passing airflow. However, in this report, a broader interpretation will be used in which all winter clouds over mountains with any potential for precipitation are considered orographic. Such clouds range from small "cap clouds" just above or enveloping the top of a mountain ridge to those portions of widespread cloud systems that are associated with mountains. The latter systems are chiefly produced by gradual uplift from cold fronts or troughs and may extend for hundreds of kilometers. However, such systems have an orographic component embedded within them wherever additional uplift is produced by the disturbance of orography on the airflow. Rangno (1986) refers to such systems as "orographically enhanced." These uplift zones can produce large maxima in liquid water production that are very important for cloud seeding potential. In this report orographic clouds will include those portions of larger cloud systems that have mountain-induced liquid water and precipitation processes operating within them.

If the associated cooling of the lifted air over a mountain barrier results in the relative humidity exceeding 100 percent, tiny liquid droplets will condense from the water vapor in the air. These droplets, much like those found in a fog, will result in a visible cloud. If the cloud is colder than 0 °C, the droplets will be supercooled, that is, colder than the freezing point of bulk water but still liquid due to their small sizes. The terminal velocity of the tiny droplets is very low so even slight upward motion in the atmosphere can keep them suspended. These supercooled water droplets will not freeze unless they get very cold (around –40 °C), condense on or contact a small foreign particle (an ice nucleus) that can cause them to become a ice crystal, or freeze onto a larger and faster falling ice particle that collides with them. Natural ice nuclei often are effective in creating ice crystals in supercooled liquid clouds colder than about –20 °C but not at warmer temperatures. The –20 °C value is only an approximation as the concentration of natural ice nuclei, effective at any given subfreezing temperature, can vary significantly with space and time. Moreover, processes that are not highly temperature dependent may be producing ice crystals (Hobbs and Rangno, 1988). But, in general, observations have indicated that winter orographic clouds with warm top temperatures tend to less effective producers of ice crystals than clouds with cold tops.

2.2 Seeding of Winter Orographic Clouds

Cloud seeding involves the formation of ice crystals in clouds that are supercooled but have few natural ice nuclei (natural ice nuclei are typically very tiny clay particles). In general, such clouds are between 0 and about –20 °C, though the colder limit can vary markedly. In order for precipitation to occur, a small fraction of the droplets must be converted to ice crystals. The crystals will grow rapidly into snowflakes at the expense of surrounding droplets inside a supercooled liquid cloud. That is because the saturation vapor pressure is higher over water than over ice at any temperature below 0 °C. Consequently, molecules of water vapor migrate to the ice crystals, which may result in evaporation of nearby droplets. Furthermore, the growing ice crystals may collide with many cloud droplets due to the higher fall velocity of the larger crystals, resulting in additional growth by freezing of the droplets onto the crystals. This growth process is called accretion or riming and can result in snow pellets (also called soft hail or

graupel). Aggregation is yet another growth process for ice crystals in which many small crystals chain together into large snowflakes.

The concentration of ice nuclei required to optimize seeding is a complex function of SLW availability, temperature and time dependence of crystal nucleation by the ice nuclei, ice crystal growth and fallout rates, distribution of SLW relative to the topography, and other factors. These complexities are best dealt with in a numerical model. However, seeding usually must be able to create at least several ice crystals per liter at prevailing temperature and moisture conditions in order to have any significant impact on snowfall rates. For example, the data of Super and Heimbach (1988), from January 15, 1985, indicated that seeding created about 10 to 20 ice crystals per liter over the target area with typical liquid water contents of about 0.1 g m^{-3} and cloud temperatures near −10°C. Yet calculated precipitation rates at the lowest aircraft sampling level were only about 0.06 to 0.09 mm h^{-1} and there was no clear evidence that the seeding decreased the cloud SLW. Model calculations by Young (1974) and others also suggest that it is unlikely that significant snowfall rates can be achieved under most cloud conditions with less than about 10 effective ice nuclei per liter. Significantly higher concentrations often may be required to optimize conversion of cloud water to precipitation.

Snowflakes can settle to the ground if they grow large enough and fall far enough before being carried downwind of the mountain barrier. Typically downward motion of the airstream to the lee of the barrier will evaporate the cloud droplets and sublimate the ice crystals so cloud seeding involves a "race" to get snowflakes to the ground before the zone of downward motion is reached. Dennis (1980) presents a more detailed discussion of the physical processes involved in the formation of snowfall in winter orographic clouds.

The conceptual model of what is expected to happen following seeding of a winter orographic cloud has not changed markedly since Ludlam (1955) wrote his classic article on the subject. Similar ideas were restated in different form by Super and Heimbach (1983) in discussing what general statements could be made about artificial seeding. They noted that,

> "In order for cloud seeding to increase snowfall from winter clouds over mountainous terrain, several links in a chain of physical events must exist. First, seeding material must be successfully and reliably produced. Second, this material must be transported into a region of cloud that has supercooled water or ice supersaturation in excess of that which can be converted to ice by naturally produced ice crystals. Third, the seeding material must have dispersed sufficiently upon reaching this region so that a significant volume is affected by the desired concentration range of ice nuclei or the resulting ice crystals. In the case of AgI seeding, this requires, fourth, that the temperature be low enough for substantial nucleation to occur. Once ice crystals form, they must remain in an environment suitable for growth long enough to enable fallout to occur, generally prior to their being carried beyond the mountain barrier where downslope motion, cloud evaporation and ice crystal sublimation typically exist."

2.3 Feasibility Issues of Winter Orographic Cloud Seeding

In the light of current understanding of the physical processes in winter orographic clouds, a cloud seeding feasibility study should address a few basic questions. First and foremost, does excess SLW exist during significant portions of at least some winter storms? More specifically, is there a significant flux of SLW over the mountain barriers under consideration during the course of a typical winter? The flux or flow of SLW is approximately the vertically integrated amount of SLW multiplied by the mean windspeed in the layer containing the SLW. A properly conducted cloud seeding project might convert a significant

fraction, but never all, of the seasonal flux of SLW to snowfall. Thus, the SLW flux represents an absolute maximum amount of water greater than the amount cloud seeding can convert to precipitation. The fraction of SLW that could be converted to snowfall by an optimally designed and conducted cloud seeding program can only be estimated. However, if the seasonal flux of SLW over the area of interest were not a significant fraction of the seasonal precipitation that falls on the area, or of the seasonal streamflow that flows from the area, it would have to be concluded that cloud seeding potential was limited. But even limited potential might be economically attractive is some regions where the benefits of additional water are high.

Some estimate of the available SLW, the basic "raw material" for cloud seeding to be effective, should be made in a feasibility study. Fortunately, such estimates have been made practical the past several years with microwave radiometer observations (Hogg et al., 1983). These measurements of integrated SLW have been made at a number of locations in the West, including two in the Sevier River Drainage (Tushar Mountains and Wasatch Plateau).

It will be shown in section 3 that a significant SLW flux has been observed over the area of interest and over other barriers in the West. It is, therefore, reasonable to consider other pertinent questions. For example, what are the meteorological conditions (storm stage, wind velocity, stability, cloud thickness, etc.) that accompany SLW? This information relates to experimental design and to when operational seeding should be done. The spatial distribution of the SLW is important for consideration of where and at what temperatures nucleation of ice crystals is possible. Thus, it is useful to know the typical position of the SLW cloud relative to the mountain barrier.

Once the spatial and temporal distributions of SLW are reasonably understood, attention should be turned to the T&D (transport and dispersion) of the seeding agent. The T&D of both airborne- and ground-released AgI involve complex processes of airflow and turbulence near rugged terrain. In addition, recent work over the Wasatch Plateau has demonstrated the importance of even weak embedded convection in the T&D of valley-released AgI.

Once the ability has been demonstrated to routinely transport AgI to the SLW zone in appropriate concentrations, other questions remain. The volume filled with AgI, nucleation rates, and subsequent ice crystal growth and fallout rates all need to be considered. It should be documented whether a significant fraction of the crystals grow to snowflakes or snow pellets which fall to the surface before sublimating in the lee of the barrier.

3. REVIEW OF RELEVANT LITERATURE AND WEATHER OBSERVATIONS

As noted above, both experimental and operational winter cloud seeding have been conducted in Utah. Experimental seeding refers to projects with the primary aim of increasing knowledge rather than water. The purpose of such projects is to continue to improve existing technology. On the other hand, operational projects apply existing technology for the purpose of enhancing precipitation and streamflow. However, research can be "piggy-backed" on operational programs to evaluate their effectiveness and to suggest means of improving them. The Utah/NOAA cooperative research program is an excellent example of this approach. Analyses of both operational and experimental seeding programs have provided a substantial amount of applicable information for the current study.

3.1 Statistical Evidence

Published statistical analyses of past Utah seeding programs will be examined realizing that such analyses are frequently inconclusive, especially when applied to operational projects. The difficulties of nonrandomized operational program evaluation are well known; for example, see Dennis (1980). Earlier experimental programs that were randomized often had serious design flaws in light of today's knowledge. In some cases the complexity of transport and dispersion was underestimated and there is serious doubt that the clouds were routinely seeded with sufficient concentrations of ice nuclei. The same flaws likely have often existed in operational programs.

A number of statistical analyses have been reported from Utah, mostly dealing with operational seeding projects. An exception is the evaluation by Hill (1979) which described two randomized winter seeding experiments in the northern Wasatch Mountains near Logan. The first seeding experiment, conducted during the winters of 1969-70, 1970-71, and 1971-72, used aircraft seeding with pyrotechnic flares containing AgI. Three mountain-top AgI generators were operated for the second experiment during the winters of 1973-74, 1974-75, and 1975-76. Briefly, the results of these experiments were mixed. The aerial seeding experiment showed no statistically significant increases. More encouraging but still not significant results were found for the ground based seeding program.

A major problem with the design of the northern Wasatch experiments was the use of 500 mb (approximately 18,000 ft m.s.l.) temperatures and rawinsonde-estimated cloud-top temperatures as indicators of cloud seedability. This was a common approach at the time before routine observations of cloud SLW were practical. It was believed that clouds with warm tops were more likely to be seedable than cold-topped clouds (Grant and Elliott, 1974) since the latter should have more abundant natural ice nuclei (both artificial and natural ice nuclei are very temperature dependant but the former are more effective at warmer temperatures). An attempt to resolve this problem was to use aircraft icing reports as indicative of cloud seedability (this approach was later expanded upon by Hill, 1982a). When precipitation data were stratified by this parameter and the results of both the aerial and ground seeding programs were combined, seasonal increases of about 15 percent were suggested. It appeared that most of this suggested increase was derived from approximately one-sixth of the winter storms. However, the tentative nature of these suggestions was stressed along with the need for verification (Hill, 1979).

A second major problem with the experimental designs of the two northern Wasatch programs likely was inadequate dispersion of the seeding material. Crosswind spacing between the three mountain-top generators was about 11 and 18 mi, respectively. Based on observations of AgI plumes from other high altitude generators (Holroyd et al., 1988; Super and Heimbach, 1988), it seems unlikely that most of the cloud volume upwind and over the Wasatch target area contained AgI with that much distance between release points.

Hill (1980a) reported on the results of measurements of the dispersion of aircraft-released AgI during nonconvective winter storms over the northern Wasatch Mountains. He concluded that both vertical and horizontal dispersion were "much lower than that desired for effective seeding."

Thus, while the statistical analyses of the two northern Wasatch seeding experiments were inconclusive, examination of them in light of current knowledge suggests possible physical reasons for that result.

Cloud seeding has been conducted in some portion of Utah each winter since the 1973-74 season with the exception of 1983-84 (Griffith et al., 1991). The first analysis of this long-term program published in the open scientific literature was by Hill (1978) who considered only the first two winters. He developed a predictor technique using rawinsonde upper air and precipitation observations for seven unseeded seasons. Hill concluded that there was little evidence to support or reject any change in precipitation due to the seeding, and that any effect, if present, was likely less than 10 percent over the whole area. Of course the data set was quite small at the time, making evaluation difficult.

Thompson and Griffith (1981) presented a *post hoc* statistical evaluation of the first 7 years of the Utah operational project for central and southern Utah, including the Sevier River basin. Both ground generators and seeding aircraft were used until 1979. Thereafter only ground releases of AgI were made. Thompson and Griffith compared precipitation measurements in the target with control areas, both during the seeded winters and for several winters prior to seeding. This common evaluation approach for operational projects must assume that the target-control relationship did not change from the nonseeded period to the seeded period except as the result of any seeding effects. The authors concluded that primary target precipitation increases of between 13 and 20 percent were indicated.

Hill (1982b) reviewed the operational seeding program for approximately the same period but included the eighth winter as well. His evaluation used not only target-control relationships from precipitation gauges (with two different control areas), but also other covariates such as upwind surface pressure and upper air observations. Hill's analysis questioned the apparent seeding increases shown in the precipitation data based on historical regression techniques. This was partially due to the apparent increases being randomly distributed between seeded and nonseeded days when various control sites were used. Moreover, Hill used control precipitation gauges along the California coast to show that, relative to the available historical records, precipitation increased eastward form California to Utah during the seeded period, especially during the years 1978, 1979, and 1980. These departures in the historical precipitation pattern appeared to be due to causes other than seeding. This finding raises doubts about the stability of the target-control relationships, and, hence, evaluations based on historical precipitation data.

Griffith et al. (1991) recently reviewed 13 winters of operational seeding in central and southern Utah, including the Sevier River Basin. The authors work for the company that has conducted the operational program in Utah for many years and are very familiar with the project. Their analysis included the 1973-74 through 1982-83 winters and the 1987-88 through 1989-90 winters. No seeding was conducted during the 1983-84 winter and only one county was seeded the following three seasons. Actually, only two widely separated counties in central and southern Utah were seeded during the 1987-88 winter so it is surprising that it was included in the "seeded winter" list. The basis of this analysis was the use of a historical regression relationship between the target and a control area for several winters prior to the seeded period. Results indicated that for the primary target area, which includes a large portion of the Sevier drainage, seeding produced an 11-percent increase in seasonal precipitation. The ratio of observed to predicted target area precipitation (predicted calculated from the target-control regression equation for nonseeded winters) was greater than 1.0 for 12 of the 13 winters. Values ranged from 0.96 to 1.29, the latter suggesting a 29-percent increase.

The third highest ratio, 1.19, was from the 1988-89 season when only two counties were seeded. Such a result would not be expected and it seems likely that causes other than seeding resulted in this large difference between the target and control precipitation. The large departure during the 1988-1989 season raises questions about the stability of the target-control relationship, similar to those raised by Hill (1982b).

Several of the control gauges used in the Griffith et al. (1991) evaluation differ from those used by two of the same authors 10 years earlier (Thompson and Griffith, 1981). For example, three Nevada gauges were used in the 1981 analysis vs. five in 1991, and five Utah gauges were used in 1981 vs. two in 1991. These discrepancies also reduce the degree of confidence that can be placed on the results of the most recent statistical analysis.

In summary, the statistical results reviewed above can not be considered conclusive, but some suggest that average seasonal snowpack increases of about 10 percent may be occurring with the Utah operational program. Similar suggested increases have resulted from analyses of some operational programs and experiments in the Rocky Mountain region. The 10-percent value is consistent with the most recent American Meteorological Society policy statement review of the Western United States quoted in section 3.4.

3.2 Physical Evidence

A considerable body of physical evidence relevant to the question of cloud seeding feasibility has been obtained in Utah and nearby States. The Utah State University program obtained a large body of physical evidence, primarily during the 1970's and early 1980's. For example, Hill (1980b) developed seeding criteria based on measurements of SLW, precipitation, cloud top temperature and vertical air motion. Hill and Woffinden (1980) developed a balloon-borne instrument ("cloudsonde") for measuring vertical profiles of SLW. Observations with this device were used by Hill (1986) to show that, "upward vertical motion and supercooled liquid water are found most often in a vertical zone from about 500 m below the barrier crest to about 2500 m above with a median height of between 500 and 1000 m above the crest." The existence of most SLW at low levels above the windward slope and crest of the barrier also was documented by Hobbs (1975a) for the Cascade Mountains of Washington, by Heggli et al. (1983) and Heggli and Rauber (1988) for the Sierra Nevada, and has been shown over different ranges in Colorado (e.g., Holroyd and Super, 1984). Knowing that most SLW tends to be in this region is of considerable importance when attempting to target the SLW with AgI. Since most of the SLW is near the barrier surface, produced by the maximum vertical motions of forced airflow over the mountain (at least in the absence of convection), it is more likely that ground-based seeding can succeed in providing ice nuclei to the SLW. On the other hand, cloud temperatures near the barrier sometimes will be too warm for significant nucleation by AgI. Typical generator outputs and plume dispersion will result in low concentrations of effective ice nuclei at temperature warmer than about −8 °C, using conventional solutions and seeding rates.

Field research has been conducted in Utah under the Utah/NOAA Cooperative Program early in each of the years 1981, 1983, 1985, 1987, 1989, 1990, and 1991. Field efforts were between mid-January and mid-March and lasted from 6 to 8 weeks. All but the 1990 and 1991 field projects were carried out in the Tushar Mountains of southern Utah near Beaver. The limited 1990 observational program and more extensive 1991 field project were conducted on the Wasatch Plateau of central Utah near Fairview. Portions of both experimental areas drain into the Sevier River system so the observations have direct relevance to this feasibility study.

Only limited analysis of the recent Wasatch Plateau measurements has been accomplished. However, some initial impressions will be noted throughout the following discussion by the lead author of this report who was involved in the Wasatch Plateau field efforts.

A final report by Hill (1982b) discusses the first Tushar Mountains field effort and resulting findings. Final reports edited by Long (1984, 1986) and Huggins (1990a), plus a final report authored by Huggins (1990b), all present results from more recent field projects in the Tushars. Several conference papers and journal articles have dealt with specific findings in detail (e.g., Huggins et al., 1989; Long et al., 1990; Sassen et al., 1990; Uttal et al., 1990).

Since results from the Tushars are well documented in final reports and publications, only the major highlights will be given here. The main emphasis of most Tushar field programs was to describe the spatial and temporal distributions of SLW in orographic clouds and to understand the physical processes that produced and depleted the SLW. It was appropriate to first consider the availability of SLW since it is needed for cloud seeding to be effective.

3.2.1 Supercooled liquid water observations. - A rather consistent portrayal of SLW distributions has emerged from the Tushar Mountain observations. This portrayal is in good agreement with impressions gained on the Wasatch Plateau during early 1991, and with published results from locations near Utah. Examples of other recent studies of SLW in the intermountain West include results from the Park Range of Colorado (Rauber et al., 1986), the Grand Mesa of Colorado (Holroyd and Super, 1984; Boe and Super, 1986; Thompson and Super, 1987), and the Mogollon Rim of Arizona (Super and Boe, 1988a; Super and Holroyd, 1989). Supercooled liquid water investigations from as far away as California (Heggli and Rauber, 1988) are in general agreement with the Utah portrayal discussed below.

Most of the Utah measurements were made by microwave radiometers. However, lidar observations of the base of the liquid cloud, aircraft measurements of cloud water content, "cloudsonde" data on the vertical distribution of SLW and surface icing probe observations all have added to the overall representations of SLW episodes. The first point is that SLW was observed for many hours each winter. Most storms had at least some SLW present during portions of their passage.

Vertically integrated values of SLW were below 0.1 mm more than half the time that cloud liquid was observed. A value of 0.1 mm is equivalent to only 0.1 g m^{-3} if the water is uniformly distributed through 1 km depth of cloud. Thus, liquid water amounts often are limited. Nevertheless, the high frequency of occurrence of low SLW values results in these periods producing a large fraction of the seasonal SLW flux. Occasionally, 15-min means of SLW exceeded 0.5 mm, and rarely 1.0 mm. These less frequent periods with abundant SLW usually resulted from convection. The wetter periods also produce a large fraction of the seasonal flux, so neither the many hours with limited SLW nor the infrequent hours with abundant SLW should be ignored by a seeding project.

The base of the liquid cloud was most often at or below the 3500-m m.s.l. crest of the Tushar Mountains (Sassen, 1985) with a corresponding temperature generally between −5 to −10 °C. Liquid bases were rarely more than 1000 m above the crestline. Analysis of saturated layers from rawinsonde data, presumed to contain most of the SLW, indicated such layers seldom extended more than 2000 m above the crestline. Observations of AgI plumes from high altitude sites have indicated most of the seeding material is found within 700 m of the barrier in the absence of convection (Holroyd et al. 1988). Assuming the situation is similar for the Tushars, the SLW zone sometimes would be too warm for effective nucleation, expected to occur at cloud temperatures colder than about −8 °C. The exact temperature at which an adequate concentration of ice nuclei will exist is a function of several variables including generator output and the

effectiveness curve for the type of AgI used, active modes of nucleation and their rates, dispersion of the seeding agent, etc. However, storms with higher SLW amounts tend to be warmer which compounds the potential problem of providing insufficient ice nuclei. But these warmer, wetter storms also tend to have embedded convection present. Impressions gained during the 1991 field season strongly suggest that convection can transport AgI from even low-level valley generators to altitudes well above the barrier where temperatures may be cold enough for nucleation.

Larger SLW amounts tend to occur with shallow clouds having warm tops that often are inefficient precipitation producers due to a lack of natural ice crystals. Deep clouds with high, cold tops generally produce high concentrations of ice crystals which can settle through the SLW condensate produced near the mountain slopes and convert much of it to snowflakes or graupel. Huggins et al. (1989) showed evidence for this tendency in that mesoscale bands had 2 to 4 times higher precipitation rates than adjacent periods between bands but the latter had greater SLW amounts. This suggests considerable variability in storm seedability not only from storm-to-storm but throughout a storm passage. Similar variability was shown by Rauber et al. (1986) and Heggli and Rauber (1988). The bands shown by Huggins et al. (1989) were only 5 to 15 km wide. Similar structure has been shown for winter storms over the Cascade Range in Washington, the Sierra Nevada of California, and the Mogollon Rim of northern Arizona.

As discussed earlier, the flux of SLW over the crest of a barrier represents the absolute maximum amount of liquid that seeding could convert to ice crystals. Only a fraction of the ice crystals might reach the surface as additional snowfall. Thus, seeding-induced precipitation will never exceed the SLW flux over a barrier, but will be some fraction of that flux. The specific fraction that can be converted to precipitation would be expected to vary with storm conditions and seeding effectiveness and is difficult to quantify with present knowledge.

Estimates of SLW flux were made for several Tushar data sets. Rauber and Grant (1987) estimated the amount of SLW passing the crest for a single storm in February 1983. This was done with rawinsonde wind data for the elevation of the barrier crest and scanning microwave radiometer measurements collected about 20 km west of the crest at a much lower elevation. It was necessary to normalize the radiometer data to the zenith so the observations may not totally represent conditions over the crestline. However, precipitation was very limited so most of the flux should have passed the downwind crestline as excess SLW. The resulting estimate of total SLW flux for a 13-hour period was equivalent to approximately 13 percent of the mean annual runoff from the Beaver River which drains the west slopes of the Tushars (the east slopes drain into the Sevier River). This case study appeared to have substantial seeding potential.

Long (1986) reported on early 1985 data from the Tushar Mountains, also based on microwave radiometer and rawinsonde windspeed measurements. During this season, the radiometer was at a significantly higher elevation than during 1983, located only about 5 km west of the barrier crest. Similar data were presented by Huggins (1990a) for the 1987 field season when the radiometer was located at the same site as in 1985. Liquid water flux estimates for early 1989, given by Huggins (1990b), were again for the west slope radiometer site used the previous two observational seasons.

During the above noted Tushar field programs the term "storm" was used to designate a period with significant cloud cover over the research area perceived to have some probability of producing precipitation. As a minimum that meant a broken to overcast mid-level or lower level cloud deck. Research periods coincided with storm periods. It is of interest to consider a summary of SLW flux estimates for storm episodes during the 1985, 1987 and 1989 seasons. This provides the beginnings of a "climatology" of possibly seedable events over the Sevier River Basin. While only three relatively short field seasons are involved, actual SLW observations are much more relevant to the question of seeding

potential than precipitation observations to be examined later. However, precipitation measurements have the advantage of being available for complete winter seasons over many years.

Table 3.1 has been extracted from the previously cited final reports for the 3 years in question with precipitation data for 1989 supplied by Huggins (personal communication). The mass of SLW passing over each meter of ridgeline of the Tushars has been estimated for all storms with any microwave radiometer observations (seven storms had no data). The beginning date of each storm and its duration are noted in columns 1 and 2. Whenever SLW data were missing for part of an episode it was assumed that the observations for the fraction of the storm measured (column 3) were representative of the entire storm duration and the estimated mass of SLW was adjusted accordingly (column 5). storm precipitation totals (column 4) are from the same gauge (P6) each season, located about 1 kilometer upslope from the radiometer site.

Table 3.1. - Storm total SLW flux and precipitation for three winters.

Storm begin date	Storm duration (hr)	Fraction of storm with flux obs. (percent)	Total precip. (mm)	Adjusted SLW mass (Mg* per m of ridgeline)
1985				
Jan. 21	14.8	0	1.0	-
Jan 26	17.2	0	1.0	-
Jan. 28	18.8	0	4.1	-
Jan. 29	6.6	0	0.8	-
Feb. 1	23.4	49	2.3	17.9
Feb. 3	7.8	48	0.5	3.2
Feb. 4	9.3	95	2.8	0.0
Feb. 7	7.8	100	1.8	3.2
Feb. 8	31.3	84	7.9	253.3
Feb. 12	2.3	100	0.0	6.1
Feb. 20	12.2	74	6.9	2.3
Feb. 22	8.7	27	0.5	0.9
Mar. 2	29.1	81	6.9	17.7
Mar. 7	10.3	58	0.0	12.5
Mar. 10	13.3	29	8.4	145.8
Mar. 11	5.7	47	0.3	0.6
Mar. 11	6.9	87	1.5	49.2
Mar. 12	10.8	55	4.3	16.0
TOTALS	236.3		50.3	528.7

Table 3.1. - STORM total SLW flux and precipitation for three winters. - Continued

Storm begin date	Storm duration (hr)	Fraction of storm with flux obs. (percent)	Total precip. (mm)	Adjusted SLW mass (Mg* per m of ridgeline)
1987				
Feb. 3	14.0	0	4.1	-
Feb. 10	9.5	0	1.3	-
Feb. 11	22.0	30	4.8	135.8
Feb. 13	20.0	78	13.7	212.7
Feb. 15	22.0	100	4.6	6.8
Feb. 18	5.7	0	0.0	-
Feb. 23	61.0	69	13.5	33.7
Mar. 7	12.0	88	0.0	3.5
Mar. 8	19.0	61	5.3	53.2
Mar. 13	4.5	100	3.1	124.4
Mar. 14	22.3	54	7.9	6.2
TOTALS	212.0		58.3	576.3
1989				
Feb. 2	48.0	100	29.5	409.6
Feb. 8	104.0	60	8.9	216.8
Feb. 18	50.0	62	18.8	42.4
Mar. 1	48.0	86	59.4	367.6
Mar. 5	72.0	95	2.5	11.4
TOTALS	322.0		119.1	1047.8

* 1 acre-ft of water is 1233.5 Mg (1233.5 X 10^6 gram).

Table 3.1 shows that storm total amounts of SLW flux vary widely from none to about 400 Mg per meter of ridgeline. It is seen that two or three storms produced 3/4 or more of the total SLW flux each field season. Nearly half of the early 1985 SLW flux passed over the barrier during a single 31-hour storm event while over 75 percent of the field season flux was due to only 2 of the 14 episodes with SLW data. One storm produced 37 percent of the 1987 total flux and three of the eight sampled storms accounted for 82 percent of the field season's flux. During 1989 a single storm produced 39 percent of the total flux and the second largest provided another 35 percent for a combined total of 74 percent. The cumulative distribution of SLW flux for the 1985, 1987 and 1989 field seasons is presented by Huggins (1990b) which shows that during each project, half the total flux occurred in less than 15 percent of the observational periods. Further, over 90 percent of the flux occurred in just 38 to 47 percent of the observational time during the three seasons.

While several of the storm periods with large SLW flux amounts lasted about 1 to 2 days, one lasted only 4.5 hours (March 13, 1987) and one lasted over 4 days (February 8, 1989). Variability is clearly a common element in winter storms as has been found in other locations. For example, Super and Boe (1988a) showed the total flux for 11 early 1987 storms over the Mogollon Rim of Arizona ranged from 1 to 419 Mg per meter of ridgeline. Three of the Arizona storms exceeded 230 Mg per meter crosswind and the rest were under 95 Mg per meter. Similar amounts and distributions are seen in table 3.1. Thus, a few storms each winter have considerable SLW flux while all others have only limited flux.

It can be expected that seeding potential also will vary considerably, and only partially because of variations in SLW. Considerable variation can be expected in the success of delivering ice nuclei to the SLW cloud due to T&D variability, temperature dependence of AgI, time available for nucleation, ice crystal growth and fallout, and other factors. The notion that seeding will result in a 10- to 20-percent increase in precipitation for each storm is erroneous. Most likely, properly conducted seeding produces relatively large percentage increases in a small fraction of the storms and limited changes in the others as suggested by the statistical analysis of the Bridger Range, Montana, Experiment (Super, 1986) and that of the Northern Wasatch projects (Hill, 1979).

Data from table 3.1 were used to investigate the relationship between storm total precipitation far up the windward slope and total SLW flux overhead. Figure 3-1 shows the plotted pairs of observations for the 27 storms with available measurements, and the linear least square regression line. It is seen that SLW flux tended to be larger in the larger precipitation producing storms. This may seem a contradiction as it might be anticipated that efficient storms would convert most of the flux to precipitation and inefficient storms would have considerable flux and little precipitation. However, the observations show otherwise. The situation in Utah is probably similar to the northern Arizona storms discussed by Super and Holroyd (1989) which had abundant SLW and limited snowfall during some (inefficient) phases and the converse during other (efficient) phases. The inefficient phases tended to be at the beginning and ending of the episodes when the cloud deck was shallow and cloud tops were warm. Middle portions of storms, associated with frontal passages, tended to have thick clouds with cold tops that apparently produced abundant natural ice which converted SLW to snowfall.

The linear correlation coefficient for the data of figure 3-1 is 0.75, indicating about 54 percent of the variance in snowfall was associated with SLW availability. While that is certainly a significant relationship, almost half the variance is unexplained. (The correlation is considerably enhanced by the two largest flux producing storms as a value of 0.45 results without them).

Similar data from 11 northern Arizona storms published by Super and Boe (1988a), plus storm total precipitation from the microwave radiometer site, were plotted on figure 3-2. A similar relationship was found with a correlation coefficient of 0.88. Again, the larger flux producing storms greatly enhance the relationship. Finding similar relationships in Arizona and Utah, with larger flux amounts associated with larger precipitation producing storms, adds credibility to the results of figure 3-1.

The median storm total precipitation for the cases plotted in figure 3-1 is 4.6 mm. All but 2 of the 13 storms with below median snowfall had limited SLW flux. The greatest flux amounts were associated with 7 of the 13 storms with above median snowfall totals. This suggests that total precipitation over the course of a storm episode can be used as crude indicator of SLW availability with little flux expected if precipitation is less than a few millimeters. However, all storms with both precipitation and flux data had some flux available if snowfall was observed. Hence, the occurrence of measurable precipitation suggests that at least some flux probably existed. Thus, it is reasonable to examine precipitation records, as done

in section 3.3.1, to approximate the frequency of potentially seedable storms over a much longer period of record than possible with microwave radiometer data.

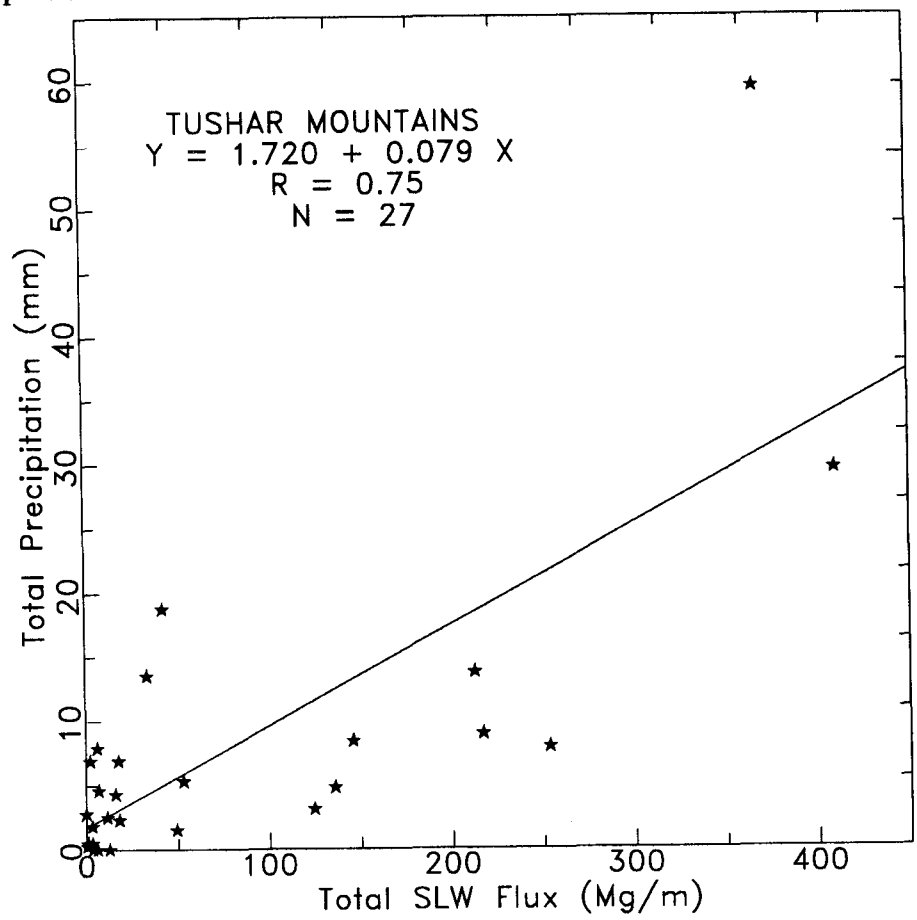

Figure 3-1. - Storm total SLW flux vs. total precipitation (water equivalent) based on 1985, 1987, and 1989 data from Tushar Mountains.

The 1985 field program in the Tushars was 2.0 months long, while the 1987 and 1989 programs were 1.5 months in duration. The average number of storms per month were 9.0 in 1985, 7.3 in 1987 and 3.3 in 1989. Huggins (1990a) classified the precipitation during the 1985 and 1987 research periods as dry and normal, respectively. A similar classification was not given for the 1989 season although Huggins (1990b) notes storms were infrequent but warm. Similar data from northern Arizona indicated 6.5 storms per month in early 1987 (Super and Boe, 1988a), a period with slightly above normal precipitation. This admittedly limited data set suggests that perhaps six to seven storms per month might be expected to pass over the Sevier River Basin during a typical winter month.

The previous discussion concerning total SLW flux per storm episode may give the impression that the only periods worth seeding have large amounts of vertically integrated SLW. In fact, Super and Boe (1988a) examined 2 months of hourly (not storm total) microwave radiometer data from northern Arizona to show that 44 percent of the total flux for the season was due to the 81 percent of all hours with mean cloud liquid water amounts of only 0.15 mm or less. Their study also shows that the 6 percent of all hours with liquid amounts in excess of 0.35 mm yielded almost 30 percent of the total flux. This suggests that seeding should be conducted whenever SLW is present, whether amounts are abundant or limited.

The former have large flux values per hour but are relatively rare. The latter are so numerous that summation of their limited flux per hour is significant over the course of a winter.

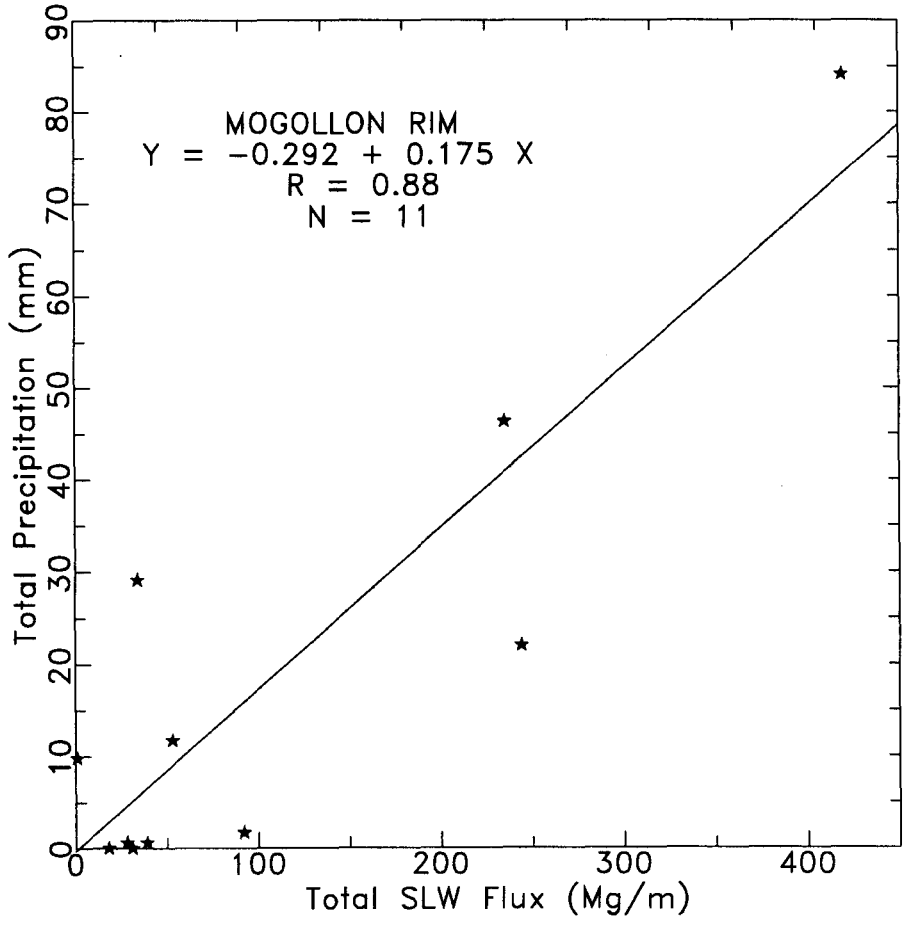

Figure 3-2. - Storm total SLW flux vs. total precipitation based on 1987 data from the Mogollon Rim.

It is of interest to compare the total SLW flux each season with the runoff from the Beaver River, which drains the west side of the 50 km north-south Tushar Mountain Range. Long (1986) gives a figure of 38,250 acre-ft for the mean annual runoff of the Beaver River. Column 3 of table 3.2 gives the total estimated flux per season from table 3.1, but in units of acre-feet for the 50 km north-south extent of the Tushars. The approximate duration of available radiometer observations, also extracted from table 3.1, is given in column 2. Assuming the 1.0 to 1.5 months of available data was representative of each entire winter allows estimates to be made of the total flux for 5.0-month winters (column 4). These estimates are admittedly crude but should yield a first approximation of excess SLW flux over the mountain range. It should be remembered that some unknown portion of the flux over the radiometer, located 5 km upwind from the ridgeline, will be naturally converted to snowfall before reaching the lee subsidence/evaporation zone. Thus, the estimates of column 4 are somewhat optimistic.

Column 5 shows the estimated 5-month flux as a percentage of the mean annual runoff of the Beaver River. (If one wishes to compare the 5-month flux values to the entire runoff from both sides of the Tushar Mountains, the values of column 5 should roughly be halved). It is seen that the 5-month flux estimates are about 1.9 to 3.7 times the runoff from the west side of the Tushar Mountains. A similar estimate was made for the west side of the lower, more gentle Mogollon Rim of northern Arizona which

yielded a value of about 32,000 acre-ft passing over 31 km of crestline in a 2-month period. That is equivalent to 1.0 times the mean annual runoff when extrapolated to a 4-month winter (Super et al., 1989).

Similar calculations for a 4-month period over the much wetter American River Basin in the Sierra Nevada showed the flux was only about 13 percent of the 1984/85 water year runoff (Heggli, 1986). However, it was estimated that 189,539 acre-ft of liquid water flux passed over the 60 km crestline of the basin, which would be equivalent to almost 158,000 acre-ft for the 50 km length of the Tushars. That value is larger than all the 5-month estimates of table 3.2, but only about a factor of two higher than the lowest Tushar value. The Mogollon Rim value, when adjusted to 50 km and 5 months, would be about 129,000 acre-ft. Thus, similar seasonal flux amounts were estimated at all three locations. The American River runoff was obviously considerably larger than that of the other drainages or its flux would represent a much higher percentage of runoff.

Admittedly the entire winter SLW flux estimates of table 3.2 may be crude because of the underlying assumptions and limited periods of observations. Nevertheless they strongly suggest that a substantial amount of excess SLW passes over the Tushar Mountains each winter unconverted to snowfall. Similar observations made over the Wasatch Plateau during early 1991 have yet to be analyzed. However, amounts and durations of SLW observations appeared approximately comparable with those from the Tushars and it is expected that similar flux estimates will result. The important point from all these estimates is that nature provides abundant SLW flux over the Sevier Basin Region that is not converted to precipitation. Thus, the required "raw material" for cloud seeding exists in abundance. The challenge for the future will be to determine what fraction of the flux can be practically converted to snow on the ground by an optimally designed and conducted seeding program.

Table 3.2. Summary of SLW flux each season compared with mean annual runoff from the Beaver River.

Season	Duration of SLW data (months)	SLW flux for period of data (acre-ft)	Est. flux for 5-month winter (acre-ft)	5-month flux as % of Beaver River mean runoff
1985	1.5	21,430	71,430	187
1987	1.0	23,360	116,800	305
1989	1.5	42,475	141,585	370

3.2.2 T&D of seeding material. - Given that abundant SLW has been documented, we will turn our attention to the T&D of the AgI seeding agent commonly used in winter orographic projects, and to information on storm stage and structure that relates to both SLW and T&D.

The effectiveness of ground-based AgI seeding of winter orographic clouds is still an open question. Hill (1982b), Long (1984), Long (1986), Huggins (1990a) and Huggins (1990b) all discuss results that suggest the low level generators used in the Utah operational seeding may not adequately target the SLW in some storm conditions. Even the use of high altitude generators does not guarantee adequate coverage by seeding plumes as shown by Reynolds et al. (1989). The delivery of appropriate concentrations of ice nuclei to supercooled cloud regions is likely the most difficult problem facing winter orographic cloud seeding. Discussion of some of the uncertainties involved with T&D has been given by Rangno (1986), Super (1990) and others. Because of these uncertainties, investigation of the T&D of ground-released seeding material was the main focus of the early 1991 field project in the Wasatch Plateau, located in the northern portion of the Sevier River Basin.

Little information is published concerning direct observations of the T&D of seeding agents from low level (valley) generators such as used in the Utah operational program. The limited evidence that exists is mostly indirect; for example, the analysis reported by Long (1984) indicated most target area snow samples, analyzed for trace levels of silver (Ag), had only background levels present. This suggests that targeting of the AgI seeding agent was frequently unsuccessful. However, direct measurements of the AgI plume, or a simulated seeding plume using a tracer gas, would provide more conclusive information.

Preliminary examination of the early 1991 data from the Wasatch Plateau, when valley-released plumes were tracked by aircraft and truck, has yielded the following indications. During some storms, or at least some storm stages, valley-released AgI was trapped into a very shallow layer by a surface-based temperature inversion. High concentrations of ice nuclei were observed near the valley floor, but transport to plateau-top levels was essentially eliminated by the stable atmosphere and calm-to-light winds. Sometimes downslope drainage winds were observed near the valley floor during storm periods which would carry seeding material away from the intended target.

During a series of storm passages during the first half of March 1991, valley-released AgI often was detected on top of the Wasatch Plateau, and several times at aircraft sampling levels 700 to 800 m above the Plateau. These were relatively warm storm sequences, generally with embedded convection present. The vertical convective motions produced abundant SLW, and apparently also transported AgI from the valley generators to well above the plateau. Concentrations of AgI, measured by continuous cloud chambers operated near −20 °C, frequently exceeded several hundred IN (ice nuclei) per liter. However, cloud chamber calibrations of the type of generator used indicate about two orders of magnitude less effective IN at −10 °C and another order of magnitude less IN at −8 °C. Thus, 500 per liter IN measured by the cloud chambers represents only about 5 per liter at −10 °C and 0.5 per liter at −8 °C. (It should be noted that the instruments used may only be semiquantitative so these values should be considered initial estimates subject to possible revision after further analysis and comparison with tracer gas measurements.)

Temperatures at 9,000 ft m.s.l. on the plateau were generally between +2 and −5 °C when SLW was present during the early March storms. The sampling aircraft often found AgI up to 12,000 ft but not much higher. With typical lapse rates of 2 °C per 1,000 ft, temperatures at 12,000 ft would be expected to range between -4 and −13 °C for the March storms sampled. If the cloud chamber IN measurements approximate actual cloud response to the AgI, cloud levels warmer than about −10 °C likely were not effectively seeded most of the time. Thus, the current impression is that convective periods are very effective in vertically transporting valley-released AgI just at the times and places that abundant SLW is being produced. However, it is not yet clear whether current seeding rates and generator spacings are routinely adequate for production of enough effective IN at the temperature levels reached.

A tracer gas was released in the mouths of two different canyons during early 1991 aircraft missions over the Wasatch Plateau. The initial impression is that this simulated seeding was successful somewhat more frequently than valley-floor seeding, but certainly less frequently than the high altitude seeding. The canyon mouth seeding resulted in relatively wide crosswind plume spreading, presumably because of flow up several small canyons that branch off the main canyons. That may offer a distinct advantage in treating a large cloud volume with a single generator.

Direct observations of the T&D of AgI from high altitude generators has been published from some sites similar to Utah mountains. For example, Super and Heimbach (1988) presented observations of AgI plumes and resulting ice particles from a seeding site well up the windward slope of the Bridger Range of Montana. All six aircraft missions documented that the AgI was transported over the target area. The

atmosphere was moderately stable in five cases and plume widths ranged from 2 to 8 km over the target about 17 km downwind of the generator. Associated plume tops were about 250 to 400 m above the highest peak in the target. The sixth case was very stable with a resulting meandering plume that was quite shallow. Since convective mixing was absent in all six experiments, mechanical mixing must have created the observed plume dispersion. In the three cases with SLW present the AgI clearly created large enhancements in the ice particle concentration and an estimated doubling or tripling of the calculated snowfall rates at the lowest aircraft sampling level. Admittedly, estimated snowfall rates within the seeding plume were very low, ranging from 0.03-0.09 mm h^{-1}. Ground observations were not available so one can only speculate about seeding effects at the surface about 600 m below the sampling aircraft.

Further evidence that high altitude ground releases of AgI can consistently result in seeding plumes crossing the mountain barrier was presented by Holroyd et al. (1988). Instantaneous plume widths had a median spreading angle of 15° and meandered with a median angle of 38°. The median height above the crest exceeded 500 m. Even so, the warmer one-third to one-half of the winter storms over the Grand Mesa of Colorado were not cold enough for adequate nucleation with the type of AgI used within the seeded zone. Perhaps convective mixing would transport the seeding material to higher, colder levels during some storms, but convective episodes were not sampled.

Preliminary indications from the early 1991 observations over the Wasatch Plateau are that AgI particles from the high altitude site were always transported over the plateau if the wind had a westerly component. The high altitude plume usually was detected at the lowest aircraft sampling level (near 12,000 feet m.s.l.) but not much higher. This suggests results were similar to studies in other mountain ranges where high altitude seeding was investigated. High altitude generator sites will succeed in targeting winter orographic clouds almost all the time. Their disadvantages include cost of installation and operation (usually remote-controlled units are required). Furthermore, it is usually not possible to target the upwind side of a mountain barrier with a high altitude generator on the same barrier because of limited time and distance for ice crystal nucleation, growth and fallout.

3.2.3 Storm structure and SLW availability. - Studies of seeded winter clouds over the San Juan Mountains of Colorado were reported by Cooper and Marwitz (1980). Based on a composite of several storms they showed that the earliest storm stage was characterized by a stable atmosphere in the lower cloud layer and low level winds that were not toward the east-west oriented barrier. Ground-based seeding was unlikely to be effective during this stage. The next stage had modest SLW with neutral stability and wind trajectories that might be favorable for seeding. The following unstable stage had a convective region developing ahead of the mountains in association with horizontal convergence. This provided abundant liquid water and a mechanism for transport of ground-released AgI into the SLW zone so this stage was judged most seedable. The final storm stage was one of dissipation and little seeding potential.

While there are similarities, the above conceptual model does not totally agree with the Utah winter storm reported by Long et al. (1990), believed representative of a significant fraction of winter storms in the intermountain West. The Utah storm also had four stages: Stage I had altostratus clouds with significant blocking of the wind by the Tushar Mountains and no appreciable SLW. Hence, seeding potential was very limited. Stage II was dominated by passage of a short wave aloft, reasonably abundant SLW and eventually a veering of the wind to approximately perpendicular to the mountains. The latter portions of this stage might have been seedable with valley generators as the low level winds should transport the AgI up the windward slopes. Stage III was influenced by a passing cold front. It had strong, deep updrafts extending from near the ground and a maxima in water condensation. Winds below the frontal surface veered from southwesterly to northerly; that is from approximately perpendicular to parallel to the

mountains. Stage III should have been seedable until low level winds became parallel to the barrier. Stage IV was one of storm dissipation and little apparent seeding opportunity.

Further analyses of the storm discussed by Long et al. (1990) was given by Sassen et al. (1990). They also presented a conceptual storm model based on numerous Utah winter storms. This model makes a clear distinction between orographic stages with shallow, moist clouds over the barrier and periods when propagating cloud systems dominated local conditions and SLW generation. Orographic storm stages are typically inefficient in precipitation production with primarily liquid water cloud present, closely related to topography. However, when mesoscale precipitation bands periodically sweep over the mountains, the SLW produced by low-level flow across the barrier is effectively converted to snowfall by ice crystals falling from the bands. The periodic mesoscale bands are a key feature that produce a large portion of the total snowfall. However, liquid-dominated clouds exist between passage of the precipitation bands which likely have seeding potential.

Three northern Arizona winter storms were presented by Super and Holroyd (1989) that are similar to the Sassen et al. (1990) conceptual model. Vertically integrated SLW amounts observed by a microwave radiometer were inversely correlated with the height of the cloud tops. When bands of high clouds with abundant natural ice crystals passed overhead, the SLW produced at low levels by uplift over the Mogollon Rim was largely converted to snowfall. However, periods with shallow clouds often had abundant SLW and limited snowfall, suggesting they were seedable. Exceptions to this general portrayal occurred when strong cross-barrier winds produced more SLW than the natural ice crystals settling from the deep clouds could totally convert to precipitation.

Reynolds and Kuciauskas (1988) discuss the structure and organization of winter storms over the central Sierra Nevada. Even though differences might be expected between the Sierra Nevada and more inland mountains, they also found highest amounts of SLW existed in warm-topped shallow clouds with embedded convection and low precipitation rates. Heggli and Rauber (1988) showed that most SLW was within about 1 km of the local terrain over the Sierra Nevada.

Based on the above and other investigations of winter storms in the West, it is expected that SLW will be concentrated in the lowest 0.5 to 1.0 km over Utah mountains, and will be most abundant when clouds are warm and shallow so that natural ice crystal and snowfall production are limited. Periods with strong cross-barrier winds or convection will have the greatest amounts of SLW while winds parallel to the plateau will produce little SLW. The passage of cloud bands with high, cold tops and abundant ice particles will reduce or eliminate the SLW produced by low-level uplift over the barrier. Considerable liquid water should be produced near times of cold front passage and whenever convection is present. The amount of the SLW available for seeding will depend upon the efficiency of natural processes in converting the water to ice. The natural efficiency can vary considerably and rapidly as mesoscale bands periodically move across the mountains.

The T&D of AgI released from low-level generators will be most effective when near-surface winds have a significant component toward the mountain barrier or when convective cells pass over the generators. From the conceptual models reviewed, it would be expected that the most favorable low-level flow would occur during the middle storm stages. The earliest storm stage likely will have blocked flow near the valley floor while the final dissipating storm stage can be expected to have low-level flow parallel to the mountain barrier. But neither of these stages appear very seedable anyway because of lack of excess SLW. High level releases of AgI can be expected to provide seeding plumes over the plateau whenever an upslope wind component exists, even when the atmosphere has a stable lapse rate.

3.3 Analysis of Blowhard Mountain Weather Observations

It is informative to consider conventional weather observations from the Sevier River Drainage as they indicate long-term averages and ranges of conditions. Moreover, as previously discussed, snowfall records provide some indication of the frequency of seedable storms.

While several weather stations exist at valley locations, information from them has little relevance to conditions high in the mountains where the seasonal snowpack accumulates each winter and melts into streamflow each spring and summer. Weather observations are rare in the high altitude portions of the Sevier Drainage because of difficulties of access. Fortunately, one climatological station has been maintained next to a radar system on Blowhard Mountain in the Cedar Breaks region, located at the headwaters in the extreme southwest end of the Sevier River Drainage. This station has provided a fairly long-term record of daily precipitation, snowfall, and temperature observations which should be reasonably representative of higher elevations in the drainage.

The data set was obtained from the National Climatic Data Center in Asheville NC. Observations consisted of 24 hour precipitation and snowfall totals, and daily maximum and minimum temperatures for the Blowhard Mountain radar (BMR, 10,700 ft m.s.l.) for water years 1965 through 1981 and from 1986 through 1989. The years 1982 through 1985 were not included because of substantial missing data. This is unfortunate in that 2 of these years were quite wet. The months of October through May were included to contain the entire snowfall season, even at high elevations.

3.3.1 Precipitation data. - As previously noted, precipitation does not relate directly to cloud seedability. However, over the daily period for which precipitation observations are available, the existence of some precipitation implies the existence of some SLW. As discussed in section 3.2.1, larger precipitation amounts imply larger fluxes of SLW. Because of this relationship, and also because precipitation observations are available over a much longer period than radiometer measurements of SLW, it is reasonable to use the snowfall data in estimating the long-term frequency of seedable conditions.

Figures 3-3 and 3-4 show the average monthly precipitation (melted snow water equivalent plus any rainfall) and average monthly summations of daily snowfall amounts (depths) for BMR for the period of record. The monthly averages are based on summations of the daily observations. It is seen that precipitation gradually increases from October through March before beginning to decline. March has the maximum precipitation with nearly 4.5 in. Snowfall depth has a corresponding March maximum of almost 45 in suggesting that essentially all March precipitation falls as snow (fresh snowfalls at mountain locations have an average density of about 0.1 so 1.0 in of snowfall represents approximately 0.1 in of precipitation). Most precipitation is in the form of snow for all months shown except October and May. A closer comparison of these two graphs indicates that the ratio of snowfall depth to water equivalent decreases to about 13 to 1 in December and January as ambient temperatures drop and returns to about 10 to 1 in February, March, and April.

Figure 3-5 shows the average number of days per winter reporting over 0.1 in (2.5 mm) of precipitation. As discussed in section 3.2.1, storms with lesser precipitation amounts generally had little SLW flux so days with less than 0.1 in are not included in any of the following analyses. The frequency of precipitation days per month is rather consistent, averaging between 6 and 8 days except for March which averages between 9 and 10 days. Since storm duration varies from several hours up to a few days (table 3.1) daily precipitation measurements only approximate storm frequency. Most storms are less than one day in duration although a storm may continue across the daily observation time for precipitation. Consequently, storm frequency would be expected to be somewhat less than the frequency of precipitation

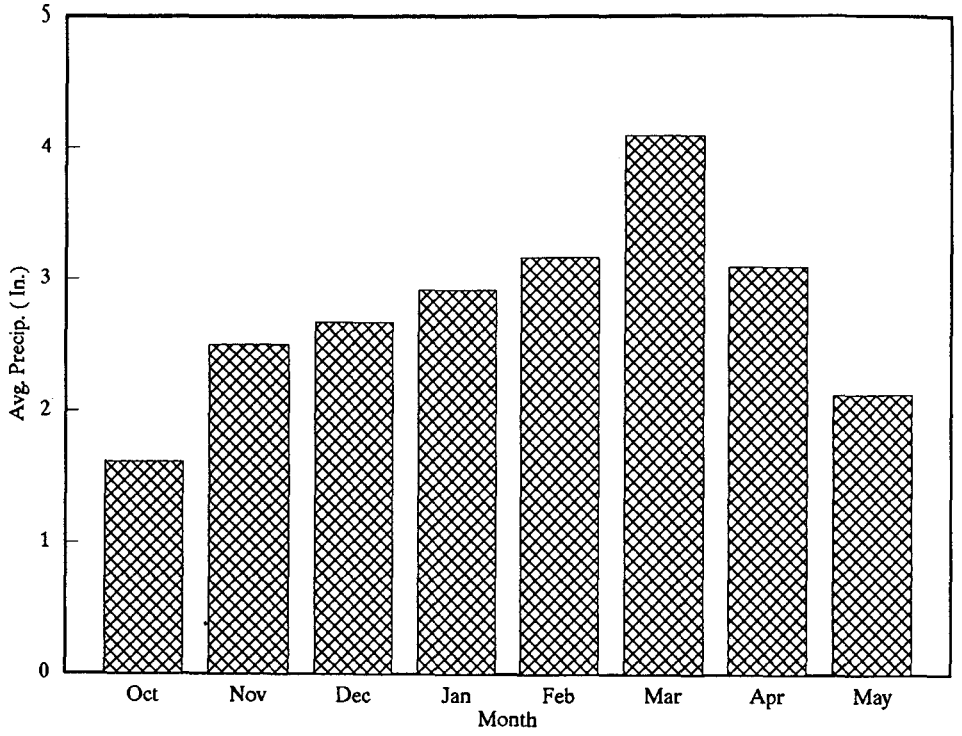

Figure 3-3. - Average monthly precipitation amounts (in) at the Blowhard Mountain radar site.

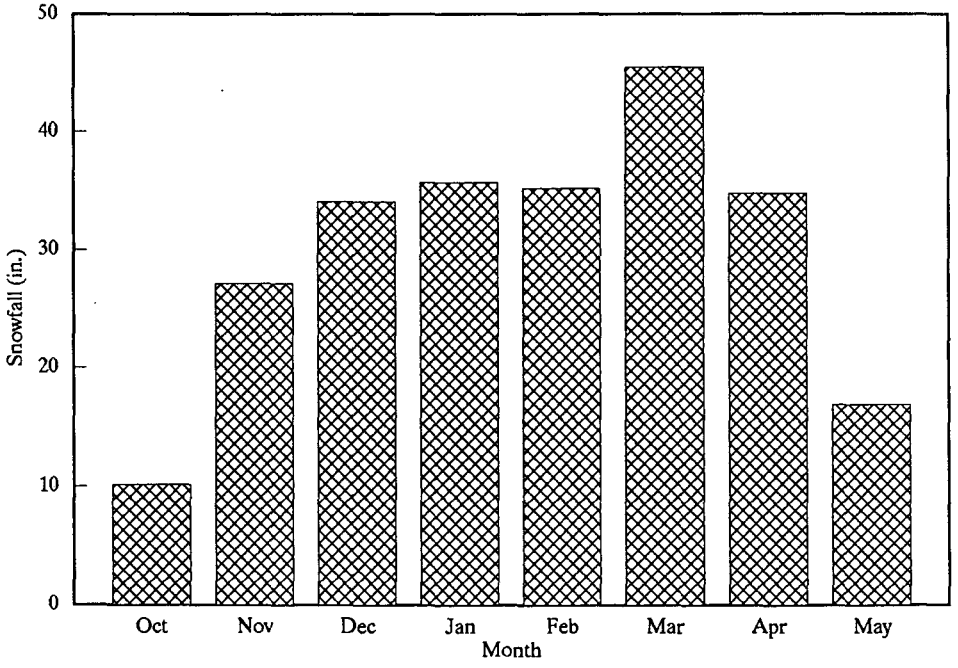

Figure 3-4. - Average monthly snowfal depths (in) at the Blowhard Mountain radar site.

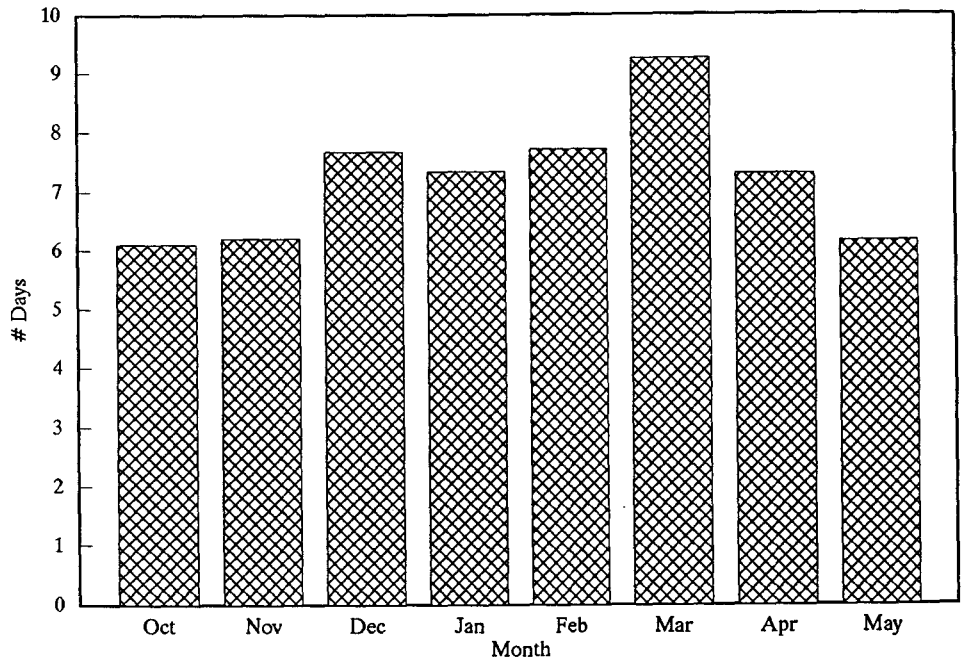

Figure 3-5. - Average number of days per month with precipitation of 0.1 in or greater at the Blowhard Mountain radar site.

days. Therefore, figure 3-5 would suggest that the typical storm frequency of 6 to 7 per month, estimated from SLW and other data in section 3.2.1, is not unreasonable but may be slightly optimistic.

Important for consideration of winter seeding operations is the number of days with precipitation versus the percentage of normal winter precipitation. Figure 3-6 shows October through May percent of normal values (both precipitation and snowfall) for the period of record (remember that the first half of the 1980's is missing). Values range for about 50 to 170 percent of normal. Thus, the maximum season had more than 3 times the precipitation (and snowfall) of the minimum winter.

Figure 3-7 compares the total number of precipitation days per season to the percent of normal winter precipitation. There is a definite relationship with a linear correlation coefficient of 0.8. The wettest winters had over 60 days with precipitation while the driest winters had less than 25 days. Hence the frequency of storm passages has a major influence on the seasonal snowpack. A normal winter season had about 45 days with precipitation of 0.1 in or more.

Precipitation is strongly related to elevation. Figure 3-8 shows a comparison of monthly average precipitation for Cedar City, BMR, and Hatch, located upwind of, on top of, and downwind of the mountain barrier, respectively. During most of the winter months the high elevation site received about 1.5 to 3 times as much as the lower elevation stations. Also there was very little difference between the two valley sites except in the spring months when Cedar City had higher monthly averages.

The relationship between precipitation and elevation can be seen in figure 3-9 which is a plot of elevation versus the mean water equivalent of the snowpack, as measured on April 1 for the years 1961-85. All available snowcourse data in or very near the Sevier River Basin are included. While considerable scatter

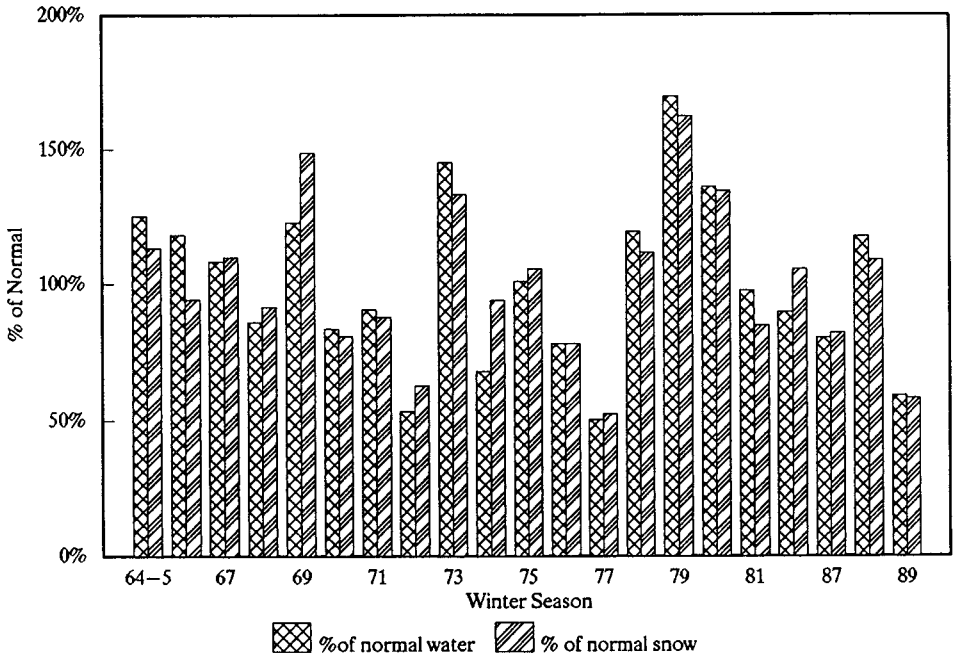

Figure 3-6. - Seasonal (October through May) percent of normal precipitation (water equivalent) and snowfall for the period.

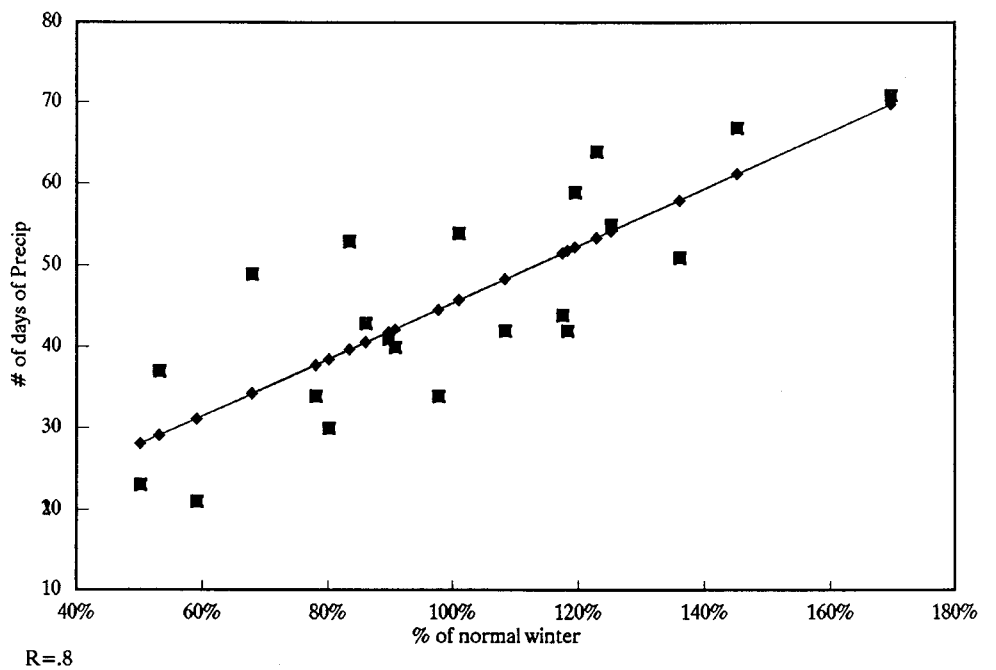

Figure 3-7. - Seasonal (October through May) percent of normal precipitation vs. number of days with precipitation of 0.1 in or greater at the Blowhard Mountain radar site.

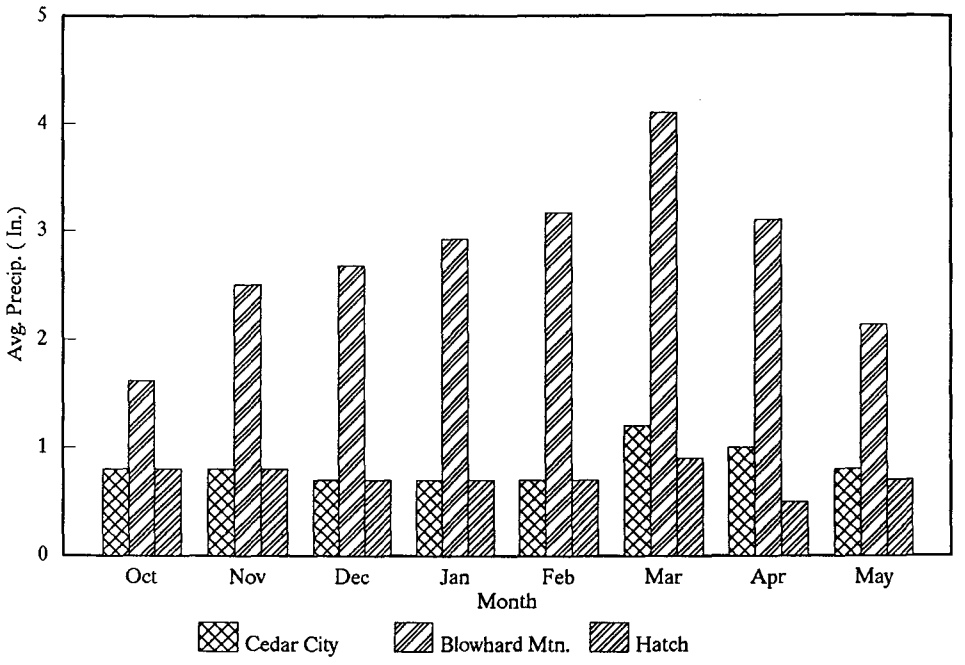

Figure 3-8. - Comparison of average monthly precipitation at Cedar City, Blowhard Mountain radar site, and Hatch, UT, located at elevations of 5700, 10,700, and 6900 ft, respectively.

exists, a linear correlation coefficient of 0.68 was calculated between the two variables. This suggests that elevation alone explains almost half the variance in snowpack water content. Other factors likely include slope and aspect of the terrain, measurement location relative to local topography and major barriers, and latitude.

Figure 3-10 illustrates the relationship between April 1 snow water equivalent and latitude for the same data set used in figure 3-9. The linear correlation coefficient was calculated to be 0.52 while the coefficient was only 0.08 between elevations of the snowcourse sites and latitude (no relationship). This indicates over one-fourth of the variance in snowpack water content is due to north-south position. Figure 3-10 shows that water equivalent increases from south to north as might be expected. The winter storm tracks are such that northern Utah has more frequent passages than southern Utah.

Figures 3-9 and 3-10 do not indicate whether the precipitation increases are chiefly due to a greater number of storm events impacting higher elevations or are because precipitation intensity is greater on higher terrain. However, based on observations from other barriers including the Tushars, higher elevations generally will have both higher precipitation rates and longer durations of precipitation per storm event.

Figure 3-11 shows the frequency distribution of daily snowfall depths at Blowhard Mountain. Over 50 percent of the snowfalls were less than 3 in and almost 75 percent were less than 5 in. Only about 1 in 10 snowfall days produced depths greater than a foot. As discussed in section 3.2.1, these infrequent heavier snowfall days would be expected to produce much of the SLW flux.

Figure 3-12 displays average precipitation, snow depth and temperature per storm event. These were defined by examining consecutive days with precipitation. The chart shows that average surface temperatures during snowfall events were below −8 °C (approximate warmest temperature for AgI to be effective as a seeding agent) four out of the 8 months. Aircraft tracking of seeding plumes and tracer

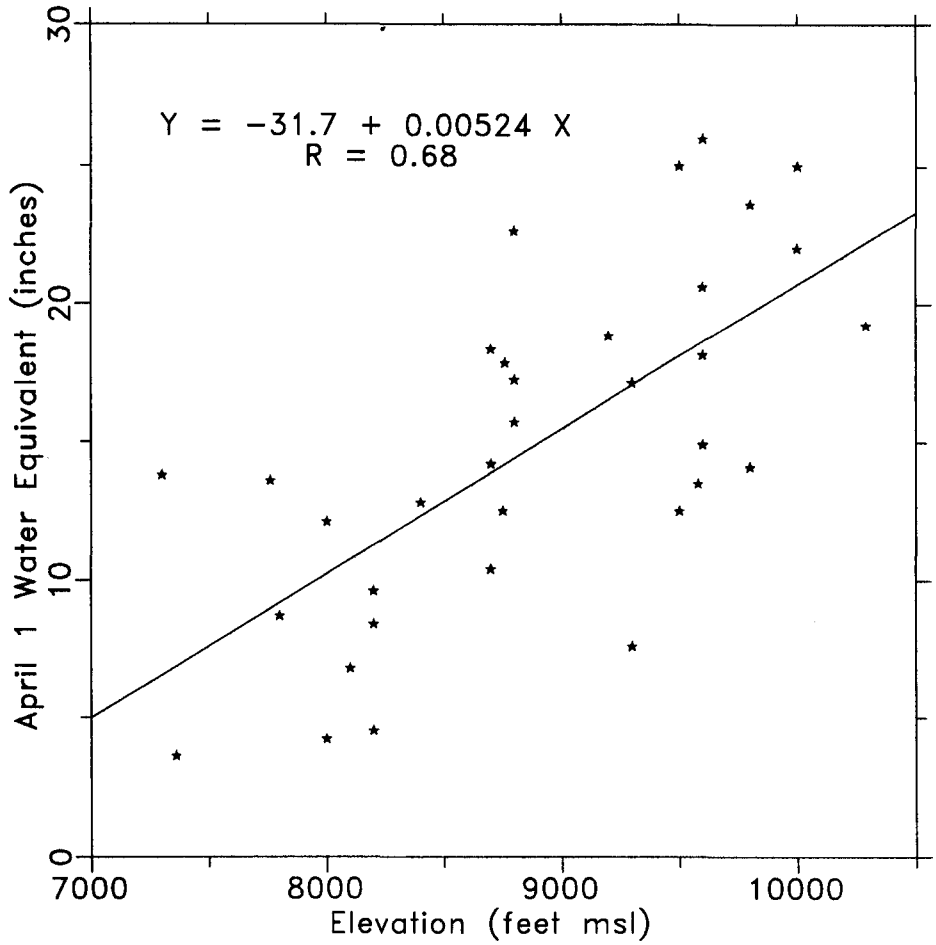

Figure 3-9. - Average April 1 snowpack water equivalent vs. elevation in the Sevier River drainage.

gases have shown that high altitude ground-released seeding material can be expected to disperse over about 600 m above the barrier crest in the absence of convection (e.g., Holroyd et al. 1988). At that elevation the cloud can be expected to be about –4 °C colder than indicated by surface observations. Thus, a Blowhard Mountain temperature of –4 °C is probably cold enough for significant ice nucleation near the top of an AgI plume passing over that location.

Much of the mountainous terrain in the Sevier Basin is below the 10,700 ft elevation of Blowhard Mountain. It is reasonable to consider the Blowhard Mountain temperatures as representative of seeding plume tops over more typical terrain. This is a conservative estimate because convection should carry the seeding agent to higher, colder levels during some storms, especially in early winter and spring. Figure 3-12 shows that a mean surface temperature below –8 °C existed from December through March suggesting most storm events were cold enough for ground-based seeding with AgI. Somewhat fewer storms would be seedable by this means in November and April and AgI ground-seeding opportunities are likely limited in October and May.

Figure 3-13 is a frequency distribution of mean temperatures during snowfall days for the 6 coldest months of the winter. Again assuming Blowhard Mountain measurements are representative of the tops of ground-released AgI seeding plumes over "typical" mountainous terrain, figure 3-13 suggests that roughly half of all days with precipitation were cold enough for effective ground-based seeding, ignoring any enhancement in vertical mixing due to convection. Similar conditions were found in Montana (Super and Heimbach, 1983) where only about half the stable storm days appeared seedable from the ground.

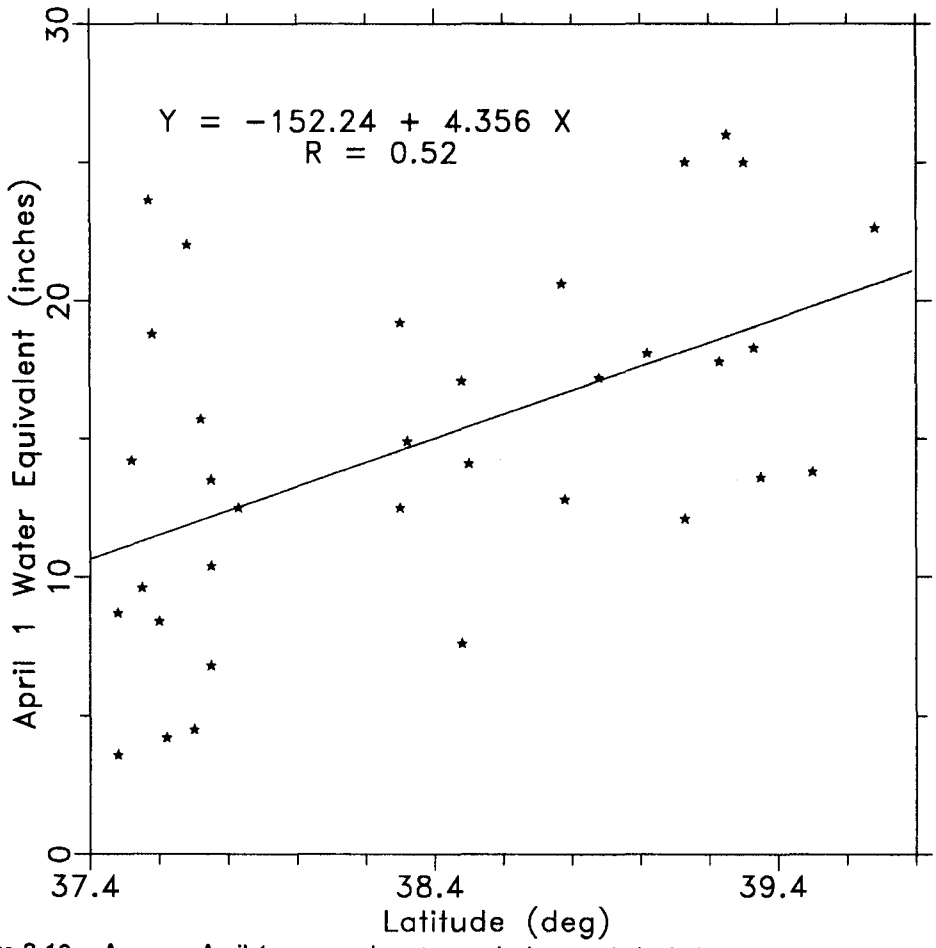

Figure 3-10. - Average April 1 snowpack water equivalent vs. latitude in the Sevier River drainage.

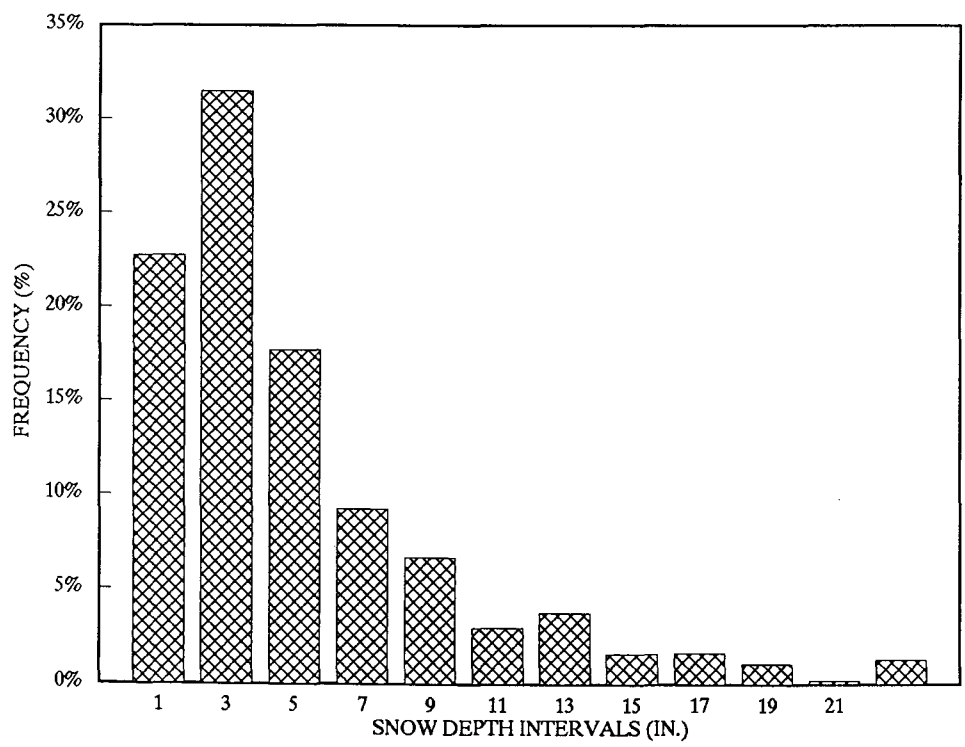

Figure 3-11. - Frequency distribution of daily snowfall depths (in) at the Blowhard Mountain radar site.

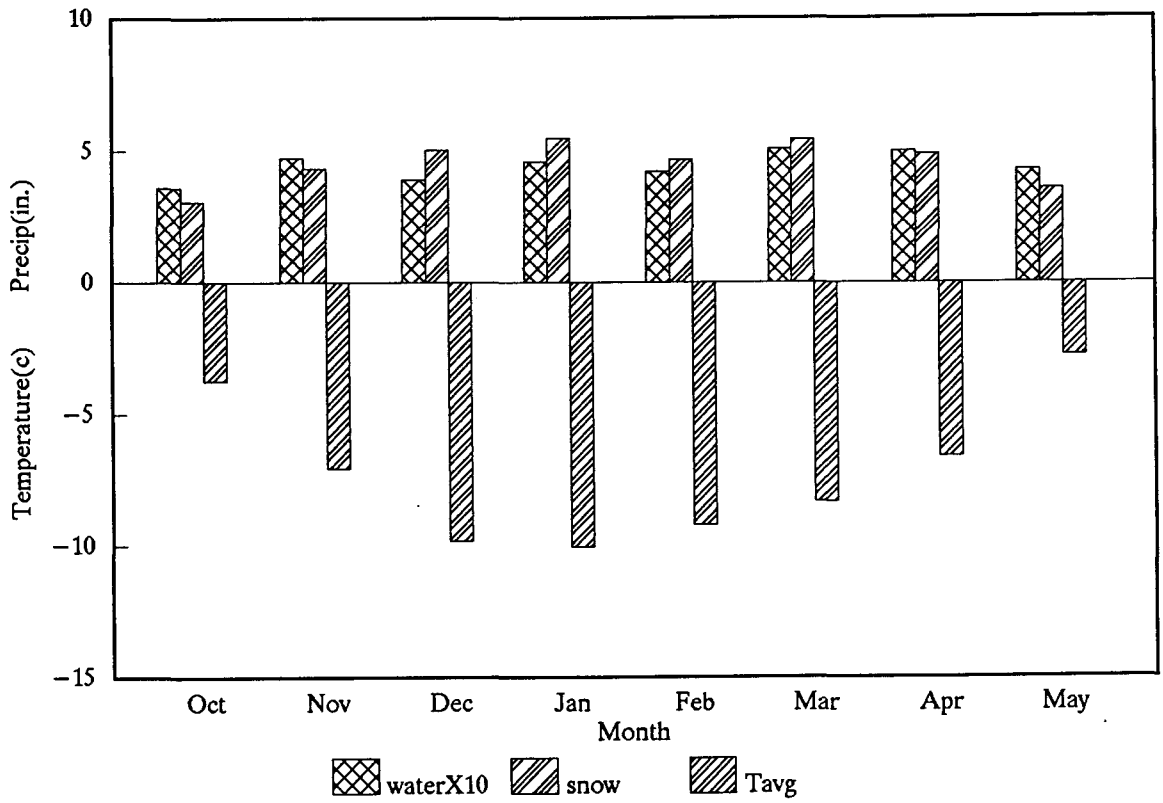

Figure 3-12. - Average daily precipitation (X10), snow depth, and temperature at the Blowhard Mountain radar site for the months October through May.

The high frequency of cases near −6 °C has interesting implications. If a type of AgI were developed that produced significant concentrations of ice nuclei at, say, −6 °C, many more storms would be seedable from the ground. The exact temperature at which various types of AgI can produce adequate ice nuclei concentrations is still open to question. Most estimates, including those in this report, are based on cloud simulation chamber results. However, conditions in actual mountain clouds may differ; for example, cloud chamber simulations are usually done with higher liquid water contents and droplet concentrations than typical of winter orographic clouds. Deshler and Reynolds (1990) indicated that a particular type of AgI may have exceeded laboratory nucleation activity in clouds over the Sierra Nevada.

The option of propane seeding (Reynolds, 1989; Reynolds, 1991) for the warmer storms deserves further investigation. It is probable that a significant fraction of Utah winter storms cannot be effectively treated with ground releases of AgI because the particles will not reach cold enough levels for significant nucleation. But propane can create ice particles at temperatures as warm as 0 °C so many more storms could be effectively treated with it. A disadvantage of propane seeding is that it must be released in cloud or at least ice saturation conditions for the chilling of the air to produce ice embryos. This requires operation of propane dispensers well up the mountainsides.

3.3.2 Streamflow data. - The main stream draining the Cedar Breaks area is Mammoth Creek. Monthly and water year streamflow data were obtained for this creek for a period of record similar to the Blowhard Mountain observations. Figure 3-14 shows the variations in water year runoff for the 1965-85 period for Mammoth Creek at Hatch. The fairly dry 1970's are contrasted to the abnormally wet 1980's. Annual runoff values ranged widely, from about 20 to 230 percent of the period's average value of 38,620 acre-ft.

Figure 3-15 compares the water year percent of normal runoff values with winter season percent of normal snowfall at Blowhard Mountain. A linear correlation coefficient of 0.87 resulted, indicating the snowfall

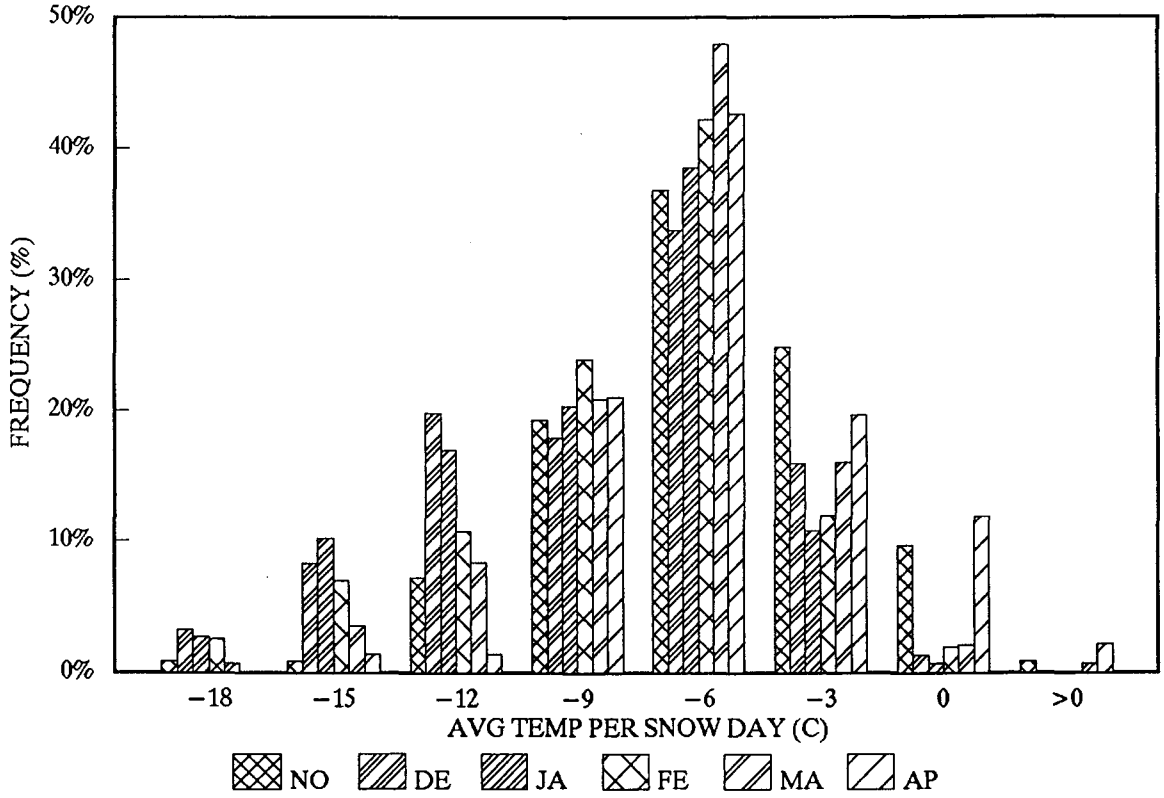

Figure 3-13. - Frequency distribution of average temperatures on days with snowfall for each month, November through April.

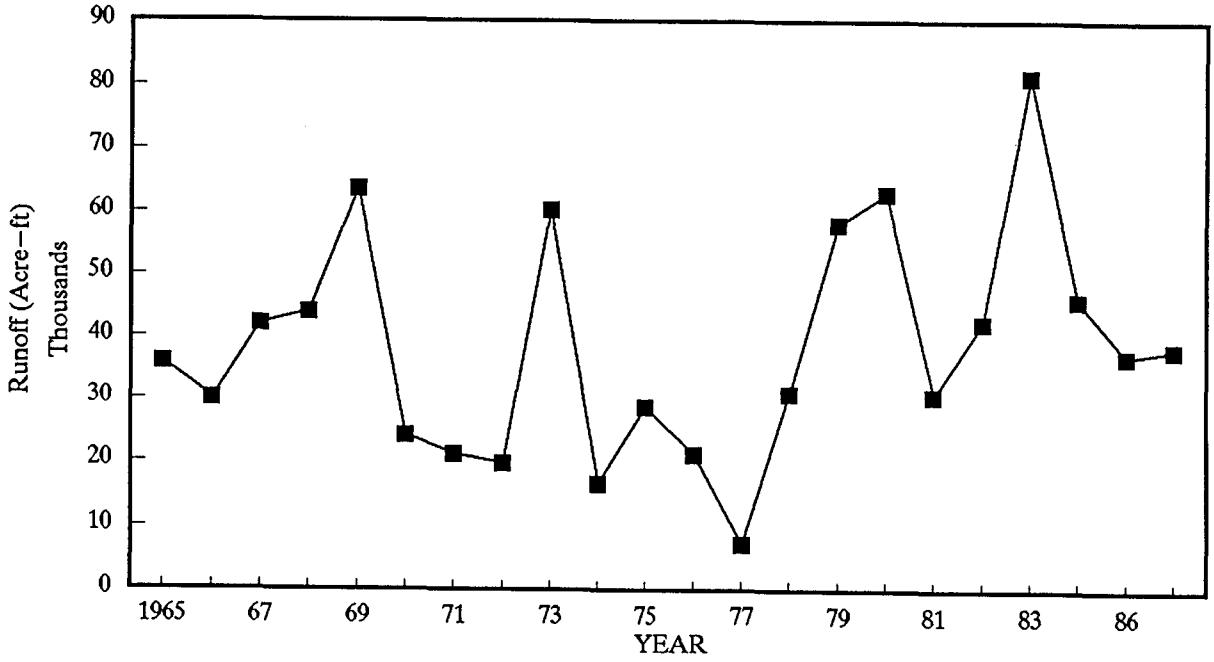

Figure 3-14. - Total yearly runoff in Mammoth Creek at Hatch, UT, for water years 1965 through 1988.

data are good predictors of subsequent runoff, explaining about 76 percent of the year-to-year variations in runoff. Clearly, enhancement of the high elevation snowpack would enhance the streamflow.

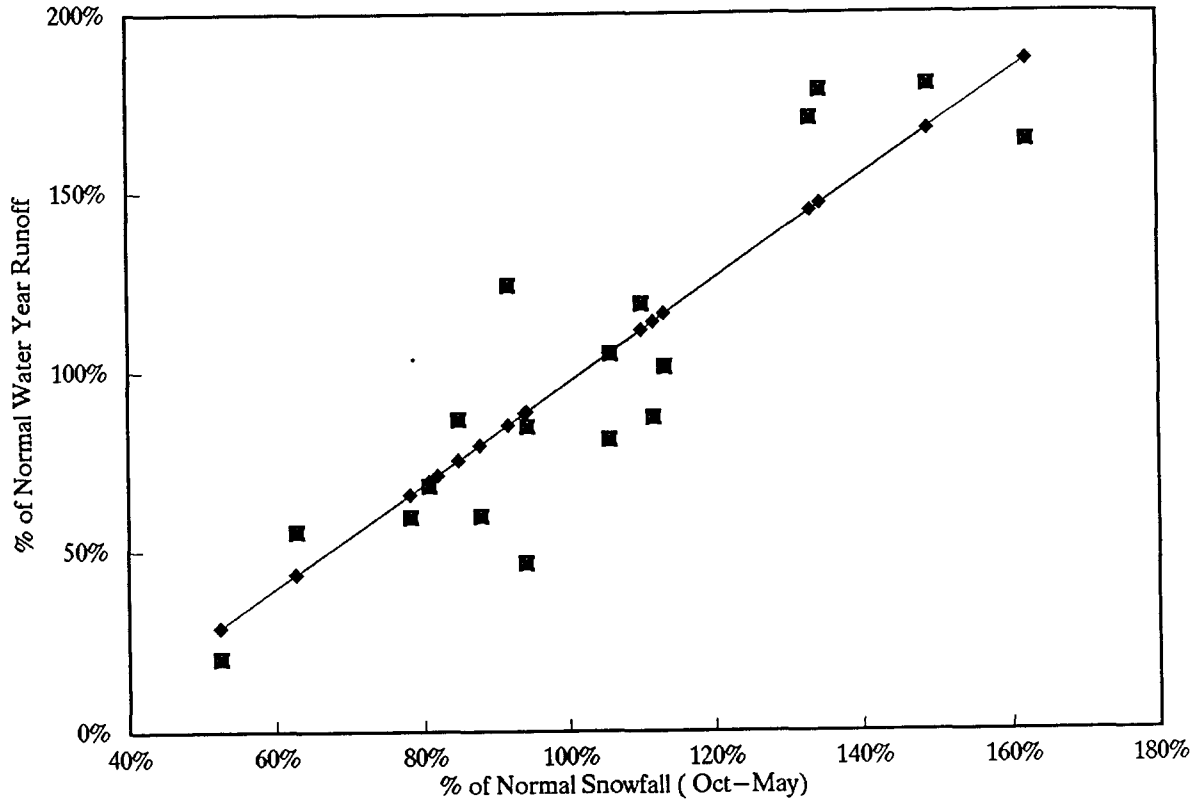

Figure 3-15. - Percent of normal water year runoff vs. percent of normal snowfall from October through May.

3.4 Summary and Recommendations

One of the goals of this study was to examine the meteorological feasibility of winter orographic cloud seeding over the Sevier River Basin. Examination of climatological weather and streamflow data indicate that several storms passages can be expected in a typical winter month in the Sevier Basin. However, there is a large range in total winter snowfall with heavy snowfall winters accumulating about 3 times the snowpack of light winters. Wetter winters clearly have more frequent storm passages. Daily snowfall amounts are highly skewed as in most mountain regions of the West with a high frequency of light snowfall amounts and a low frequency of large amounts.

Snowfall accumulation is strongly related to elevation and moderately related to latitude with northern portions of the basin receiving more snow presumably due to more frequent storm passages.

As in most mountain regions, a strong relationship exists between high elevation seasonal snow accumulation and subsequent runoff in the Sevier River Basin. Obviously, enhancement of the snowpack by cloud seeding would increase the mountain streamflow.

Previous discussion has indicated a substantial amount of SLW flux passes over the mountains of the drainage each winter. Thus, the "raw material" needed for seeding exists in abundance. The SLW tends to exist near the windward mountain slopes and over the ridges. The SLW certainly can be targeted with ground-based equipment, which may need to be located at high-altitudes to treat some storm periods.

However, temperatures in the layer that can be targeted from the ground sometimes will be too warm for significant nucleation by commonly used types of AgI. A review of T&D investigations showed that releases of AgI from high altitude sites along windward slopes would routinely result in the seeding agent reaching the SLW zone. Recent work on the Wasatch Plateau suggests that valley-released AgI will be transported well above the mountains during convective periods and perhaps at other times as well. However, further investigation of valley seeding is needed, especially during stable storms.

Aircraft seeding could, of course, be used but was not considered because of high costs and logistic difficulties. Sustained missions can be impractical during the heavy icing episodes that characterize periods with large SLW flux. Moreover, during warmer storms, aircraft AgI seeding may have the same limitations as ground seeding in attempting to provide high enough concentrations of effective ice nuclei for the warm SLW zone near the mountains. Ground-based propane seeding should be explored as an alternative to AgI seeding during warmer storm periods.

There seems to be little reason to doubt that properly located AgI generators with sufficiently high outputs can create significant ice crystal concentrations in the SLW zone within 0.5-1.0 km of Sevier Basin mountain ranges when the atmosphere is cold enough. The question is will such seeding result in significant increases in snowfall. While a number of statistical evaluations indicate a positive answer, other studies have been inconclusive. Statistical analyses should not be considered conclusive without supporting physical observations. The latter generally have been lacking in past programs.

Simple calculations of ice crystal growth rates and fallout velocities for typical conditions indicate that some seeding-created ice crystals should reach the mountain surface before passing into the downwind subsidence region. For example, on the Wasatch Plateau, characteristic distances between high altitude seeding sites and the lee edge would be about 15 km. With a 10 m s^{-1} windspeed, an air parcel would take 1500 s (25 min) to traverse this distance. If nucleation occurred near the seeding site and the resulting ice particle grew at 0.5 μm s^{-1}, it would reach 0.5 mm size and have about 0.4 m s^{-1} terminal velocity after 1000 s (Rauber et al., 1988). Ignoring the vertical motion field over the plateau, the particle could fall 200 m in the remaining 500 s before reaching the lee slopes.

Only the lowest 200 m above the plateau could be effectively seeded in the simple example just given. But nature is much more complicated than the example suggests. A sophisticated numerical model (e.g., Cotton et al. 1986), capable of calculating the motion field and microphysical processes, should be used to provide realistic estimates. For example, nucleation of ice crystals is time dependent, especially when contact nucleation is dominant (DeMott et al., 1983). Crystal growth rates vary significantly with temperature and other factors (Holroyd, 1986, estimated rates over 1 μm s^{-1} in clouds at −13 to −14 °C). Terminal velocities also vary markedly with crystal size, type, and degree of riming (Rauber et al., 1988). Overall, ice crystal nucleation and growth can be considered a stochastic process in which a small fraction of the particles will become much larger than the general population. These "fortunate" particles will contain much of the total snowfall mass and will have a greater change of reaching the surface before passing beyond the target area.

In general, stronger winds produce greater condensate (more SLW) which will enhance ice crystal nucleation and growth, but allow less time for air parcels to traverse the mountain barrier. Factors that enhance ice particle growth and fallout to the surface include temperatures ranges conducive to rapid crystal growth, abundant SLW leading to growth by riming, barriers with large along-the-wind distances, and moderate windspeeds. It is usually prudent to release AgI from as far upwind of the target as practical, perhaps even from the next mountain range upstream. This enhances volume filling of the SLW zone and allows nucleation to occur sooner.

While conditions appear favorable for seeding to enhance the snowpack of the Sevier River Basin, it must be admitted that strong physical evidence is still lacking that seeding can result in significant snowfall enhancement with economic benefit. The most recent weather modification policy statement of the 10,000-member American Meteorological Society (1985) indicates that scientific proof remains elusive for winter mountain storms in general. The policy statement notes that "Precipitation amounts from certain cold orographic cloud systems *apparently* can be increased under favorable conditions with existing technology in the Western United States. Increases of the order of 10 percent in seasonal precipitation are indicated in *some* project areas." But the policy statement cautions that "In all cases where indications of precipitation increases have been suggested, *confirmatory experiments* are required before any of the technologies can be considered *scientifically proven.* The establishment of the *physical mechanisms* active in any demonstrated modification effect is also needed to achieve general scientific acceptance" (emphasis added). There is clearly a need to provide convincing scientific evidence that winter orographic cloud seeding can increase precipitation before the emerging technology will be widely accepted as a viable option for water resources management.

It is strongly recommended that a weather modification demonstration program be conducted at a typical site in the Sevier River Basin to validate the technology and gain sound information on the methods and costs of conducting an effective operational seeding program. Until such information is obtained there will always be serious questions about the amount of additional water being produced by operational seeding. Moreover, it may be that substantially more water could be provided by a more effective seeding program. Preliminary benefit-cost ratios are estimated in section 8 but these had to be based on several untested assumptions. More definitive estimates must await improved physical evidence of seeding effectiveness.

4. DESIGN CONSIDERATIONS FOR A WEATHER MODIFICATION DEMONSTRATION PROGRAM

One of the purposes of this study is to provide a preliminary design of a weather modification demonstration program should winter clouds over the Sevier Drainage appear seedable. They clearly do appear seedable a large fraction of the time but the effectiveness of current seeding approaches has yet to be demonstrated as discussed in section 3. Accordingly, consideration has been given to an appropriate design of a weather modification demonstration program as will be discussed.

4.1 Review of Past Experimental Approaches and Recent Developments

Several statistical experiments have been conducted with winter orographic storms in the West but most produced inconclusive results. Past statistical experiments typically had a number of common characteristics. Hypotheses were stated, with varying degrees of detail, which noted the chain of physical events expected to follow seeding. In broad terms, the hypothesis would note that SLW in the form of tiny droplets would have to exist within the cloud, and seeding would have to convert some of these droplets to ice crystals capable of growing and settling to the surface as snow or melting and falling as rain. When a presumably suitable storm appeared or was forecast, a random decision was made to seed or to reserve the event as a nonseeded control case. In either event, the same observations were taken. After a number of field seasons, cases were statistically tested for treatment effects on precipitation. The entire data set might be partitioned into meteorologically similar categories; for example, by ranges of estimated cloud top temperature, and each category would be statistically tested for differences between seeded and nonseeded precipitation. Observations usually were limited to target area precipitation and some general indications of the storm structure.

Such efforts have been referred to as "black box" experiments because, if the statistical testing did not indicate significant differences between populations of seeded and nonseeded experimental units (storms, days, etc.), insufficient physical observations existed to determine where the hypothesized chain of events failed. Even when statistical testing suggested significant precipitation differences, the exploratory nature of most analyses left doubts about the estimated probabilities that the differences were not due to chance. Furthermore, uncertainties remained about the physical mechanisms involved so that transferability of results to other locations was questionable.

Even if statistical testing indicates that a particular seeding program produced significant precipitation increases, there is no assurance that the seeding method employed was highly efficient. Perhaps greater increases could be achieved with a different treatment approach. Thus, the seeding process cannot be optimized without a thorough physical understanding.

Improvements in numerical modeling of winter orographic clouds have significantly aided our understanding of airflow and microphysical processes (e.g., Young, 1974; Clark, 1977; Cotton et al., 1986; Bruinjtes et al., 1991). Incorporating observations from a particular mountain region into a numerical model adapted for that region can markedly increase understanding of the key processes involved and how seeding influences them. Less complex models can be used in real time to guide the conduct of physical seeding experiments (Rauber et al., 1988).

Reynolds (1988), in a review of winter snowpack augmentation, showed that a consistent picture is emerging between recent physical studies and suggestions from earlier statistical experiments. For example, Reclamation scientists have provided convincing evidence that the physical seeding hypothesis was correct in a limited number of experiments in recent years. Super and Heimbach (1988) were able

to confirm microphysical changes in seeded clouds over the Bridger Range that presumably increased snowfall (no surface observations were made in the limited 4-week study). Super and Boe (1988b) showed evidence of precipitation changes at aircraft sampling levels and on the surface during a 2-month study period over the Grand Mesa, Colorado. Deshler et al. (1990) demonstrated seeding induced microphysical changes at aircraft levels in about 35 percent of 36 experiments conducted over a three-winter period. Following seeding effects to the ground proved difficult in the Sierra Nevada, partially because of the impracticality of low-level aircraft sampling over the rugged mountains. Moreover, ice multiplication or enhancement (processes whereby crystal concentrations far exceed ice nucleus concentration such as described by Hallett and Mossop, 1974) is common in maritime clouds over the Sierra Nevada, resulting in large ice crystal concentrations which can mask seeding effects. However, the final Sierra Nevada experiments demonstrated microphysical effects at the surface after the targeting scheme was improved with additional observations. Deshler and Reynolds (1990) presented a case study in which the effects of aerial seeding were followed for over 90 min and 100 km.

While encouraging, the above physical experiments have been too few to demonstrate how often storm conditions permit the seeding hypothesis to operate, or how much additional snowfall might result from routine seeding. However, the need is clear to conduct a series of comprehensive physical seeding experiments, capable of monitoring all key processes from release of seeding material to precipitation on the ground. Both understanding and instrumentation are now adequate for this task. The remainder of this section will be concerned with the design of comprehensive physical seeding experiments for the Sevier River Basin. Only after such experiments are conducted and fully analyzed will it make sense to design a statistical experiment intended to document multiwinter seeding effectiveness over a large area.

4.2 Factors Important In Planning Comprehensive Physical Cloud Seeding experiments

A design plan for comprehensive seeding experiments was recently completed for the Mogollon Rim of Arizona (Super et al., 1991). It reviewed several physical cloud seeding experiments conducted over the past two decades, and evaluated the factors affecting the success of these experiments. A number of lessons became apparent in reviewing the various physical experiments, some of which succeeded and some of which did not. The following discussion reviews those lessons extracted from the noted report.

First, and not surprising, it is much simpler to document seeding effects leading to snowfall on the surface from nonprecipitating clouds than from clouds where nature is already somewhat efficient. The seeding signal can be unambiguous for clouds with low natural IPC as illustrated by Super and Boe (1988b).

Nonprecipitating or lightly precipitating periods with at least moderate SLW available are common in Utah winter storms. Radar, SLW, and precipitation rate observations over the Wasatch Plateau in early 1991 demonstrated a number of storm periods, often lasting hours, with little natural snowfall and abundant SLW. Huggins and Sassen (1990) showed very light snowfall rates and significant SLW amounts during a storm in which physical seeding experiments were attempted.

It is, of course, important to demonstrate whether seeding can produce physical evidence of enhanced snowfall when some natural snowfall is occurring but excess SLW still exists. Hobbs (1975b) showed evidence of snowfall increases during naturally light snowfall. Similar documentation at aircraft levels was given by Super and Heimbach (1988).

It will likely be increasing difficult to demonstrate that seeding enhances snowfall as natural precipitation rates increase. When nature becomes very efficient, seeding cannot increase the snowfall because all available SLW is already converted to ice. Fortunately, many Utah storms are probably similar to the

Arizona winter storms illustrated by Super and Holroyd (1989) which tended to go through alternate stages that were either efficient or inefficient. This may be common throughout the West. For example, Hobbs (1975a) indicated that clouds over the Cascades were generally in two categories, "those in which ice particle concentrations never exceeded 0.1 liter^{-1}, and those in which the maximum concentrations were no less than about 10 liter^{-1} irrespective of temperature." It seems probable that well designed physical experiments will show snowfall enhancement from naturally inefficient clouds, no enhancement from very efficient clouds, and only suggestive evidence of snowfall increases from moderately efficient clouds.

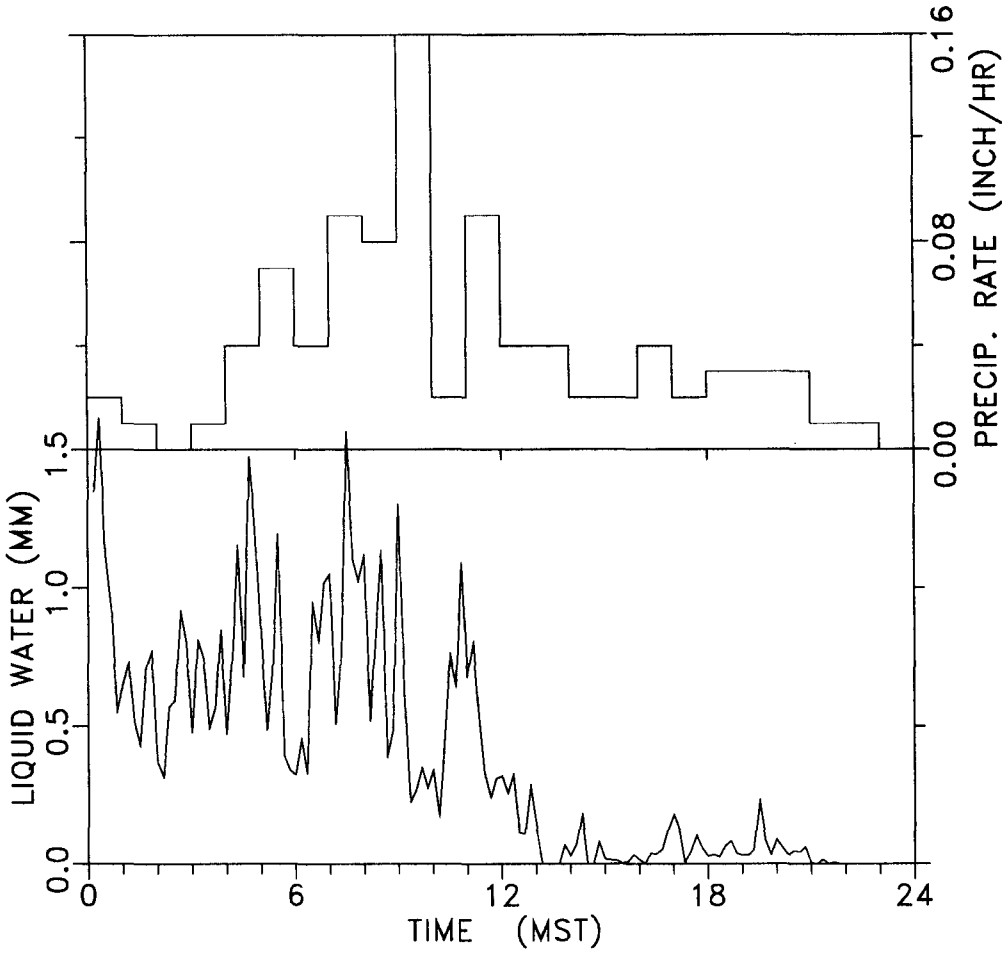

Figure 4-1. - Precipitation rate on, and vertically integrated liquid water above, the Wasatch Plateau on March 5, 1991.

Figure 4-1 demonstrates some of the complexities involved in attempting to conduct physical experiments caused by natural storm variability. The figure shows the SLW observed by the microwave radiometer on the upwind side of the Wasatch Plateau (bottom panel) and the precipitation rate measured on the downwind side (top panel) during part of the wettest storm of the 1991 season. While some valley AgI generators were on, several had problems apparently due to high winds, and little AgI was detected on top the plateau until after 1300 hours (all times m.s.t.). Precipitation rates varied from less than 0.01 in per hour to as high as 0.16 in per hour. (The latter value corresponded to a shift in wind direction and large decrease in windspeed). To put the precipitation and SLW values in perspective, the SLW flux will be estimated so it can be compared with precipitation.

The mean value of vertically integrated SLW from midnight to 0900 hours was about 0.8 mm. Winds in the SLW zone during that period were westerly and at least 15 m s^{-1}. This results in a SLW flux exceeding 12,000 g s^{-1} per meter crosswind distance. If that amount of flux were converted to precipitation of uniform depth across the approximate 10 km width of the plateau downwind of the radiometer, a precipitation rate of 4.3 mm per hour (0.17 in per hour) would result. Snowfall rates gradually approached that value after 0400 as the clouds became increasing efficient. However, precipitation rates were much lower than possible with the available SLW flux before 0400, and, with the exception of a single hour, similar low precipitation rates had existed since 2000 the previous day. This extended period with high SLW flux and very low precipitation rates likely had large seeding potential. The problem would be to separate enhanced snowfall due to seeding (a "seeding signal") from the natural variations with time. A seeding signal might have been obvious if a pulse of AgI had been released prior to 0400 but what if an AgI release had been started about 0400? Then one might have been tempted to claim as a seeding effect the apparently natural increase in snowfall after 0400.

Obviously other data must be examined that are unaffected by seeding but related to snowfall rates in the target in accessing the reality of seeding signals. For example, the decrease in SLW with time in figure 4-1 was associated with an abrupt decrease in windspeed after 0900, and a veering of the wind from southwest to northwest so the airflow gradually became less orthogonal to the barrier. These wind velocity changes would be expected to provide less forced uplift and associated reduced condensate production. The atmosphere also became colder during the afternoon and the clouds appeared to be quite efficient in converting the limited liquid condensate to light snowfall.

4.3 Observational Considerations for Physical Cloud Seeding Experiments

Recent improvements in instrumentation have made it practical to monitor key physical processes, provided mountain ranges are chosen that are logistically practical for experimentation. For example, microwave radiometers can monitor SLW above mountain barriers, and two-dimensional laser imaging probes can observe vast numbers of ice particles for later computer processing. These key observations were impractical to make on a routine basis until approximately the past decade.

A very important factor common to successful physical experiments is airborne tracking of the seeded volume between the release point or line and the target area. The complexities of the three-dimensional airflow over mountains are sufficient to render suspect any windspeed and direction estimates based on upwind soundings or a few local surface measurements. It is almost essential that an aircraft monitor where the seeding material is going until it passes over the target, or is shown to have missed the target. An alternate approach would be to have sufficient ground sampling to monitor the position of a surface-released seeding plume but this is impractical in most mountain regions.

Implicit in the need for aircraft tracking is that experiments be conducted over mountain barriers where airborne sampling is practical at low levels. Some regions have serious airspace conflicts among aircraft; for example, within "Victor" routes between major airports. Such high traffic areas should be avoided in planning experiments because needed airspace blocks will frequently be unavailable.

An even more serious consideration is to avoid barriers that preclude flight near the surface. The usual restriction is that aircraft flying in-cloud must stay at least 2,000 ft (600 m) above the highest terrain within 5 miles (8 km) of the flight path. Special wavers can be obtained in some locations to allow flight within 1,000 ft (300 m) of the terrain, but either nearby navigational aids are required or a sophisticated on-board navigation system must be employed (Loran-C, inertial navigation system). Even if the target is at a relatively high elevation, nearby higher peaks may preclude aircraft sampling within a kilometer

or more above the target site. Yet a growing body of evidence shows that most of the SLW is concentrated in the lowest kilometer over the windward slope. Therefore, considerable ice particle growth can occur in this zone. This is also the zone in which most ground-released AgI is transported. So a kilometer-deep vertical "gap" between lowest aircraft observations and surface monitoring will cause considerable uncertainty in the growth, fallout and resulting targeting of ice particles resulting from seeding. For example, the early 1989 physical experiments over the Tushar Mountains (Huggins and Sassen, 1990) suffered from lack of aircraft observations because the rugged terrain made impractical low-level flight over the target site.

The ideal mountain barrier for physical cloud seeding experimentation would allow surface sampling on the crestline, would have only marginally higher peaks near the target site, would not have an abrupt crestline which could create serious downwind turbulence, and would have nearby navigational aids such as a VORTAC station. Fortunately, portions of the mountains in the Sevier Basin approximate the ideal except for nearby navigational aids.

Any physical experiment requires some targeting scheme to decide when and where to release the seeding material in the case of a fixed target, or when and where to operate the "mobile target" (usually sampling aircraft) in the case of fixed generator locations. The scheme may be no more complicated than using a typical wind velocity for the altitude range in question to estimate transport time, and typical growth rates and fall speeds for the type(s) of ice particles expected. Such approaches are sometimes referred to as "back of the envelope" calculations. On the other extreme, a highly sophisticated three-dimensional time-dependent numerical model may be run on a supercomputer to simulate the entire airflow pattern around the barrier and all important microphysical processes for expected ranges of conditions. Given the uncertainties in certain key processes and impracticality of detailed measurements around mountains, it is probably most reasonable to use a targeting model of modest sophistication that can be run on a computer in the field using real-time input data. The approach used by Rauber, et al. (1988) may be a good compromise.

If resources permit, a highly sophisticated model should be run for several combinations of atmospheric conditions believed to cover the range of winter storm conditions in the region of interest. The resulting predictions should be in general agreement with the simpler operationally used scheme or the latter might require some modification.

Another requirement for physical experiments is detection of either the seeding material or a simultaneously released tracer to document the seeded zone. Silver iodide can be tracked with an acoustical ice nucleus counter but dry ice is not traceable. Natural variations in IPC (ice particle concentration) can easily mask the ice particles caused by seeding unless the seeding material itself, or a tracer material such as sulfur hexafluoride (SF_6) gas, be independently measured to distinguish the seeded volume from natural cloud. In other words, attempting to specify the seeded volume by monitoring ice particles alone may lead to uncertain interpretation of seeding effects; for example, see Deshler and Reynolds (1990).

The most detectable characteristic of seeding at ground level is usually the IPC. Ice crystal sizes and habits, and silver content in the snow, are also suggestive that seeding affected the precipitation process. However, successful seeding usually substantially increases the concentration of ice crystals to levels well above background. Much of the IPC enhancement will likely be at small crystal sizes, less than a millimeter in diameter. Small seeded crystals are often in the form of hexagonal plates or small columns. An aspirated particle imaging probe offers a practical means of continuously monitoring ice crystal

characteristics at the surface. However, it should be supplemented by photographic documentation which provides more detailed data, though requiring considerable manual reduction.

The degree of riming was shown to have been reduced in some of the reviewed experiments. This should be a consequence of seeding if enough ice crystals are created to utilize most of the excess SLW. The degree of riming usually is not discernible from aspirated imaging probe data so manual or photographic observations are required at the surface target.

It is useful to obtain snow samples for silver analysis at frequent intervals to help evaluate seeding effectiveness. Enhanced silver levels in the snow do not prove any seeding effect directly since most or all of the silver could result from scavenging by natural snowflakes. However, finding only background silver concentrations very likely means the target was not impacted by seeding. Thus, the silver-in-snow data provide a partial check on claiming real seeding effects that are actually natural variations.

Highly sensitive precipitation gauges are needed for physical experiments because the seeding effects may be very brief (e.g., only a fraction of an hour for a single airborne line), and rates may be low with typical SLW amounts. For example, the total precipitation amounts from individual seedlines of AgI, reported by Super and Boe (1988b), ranged from 0.10 to 0.22 mm. Conventional weighing gauges have a resolution of 0.25 mm (0.01 in), and are unsuitable for physical experiments unless modified.

Radar has sometimes been used in attempts to follow the effects of seeding between lowest aircraft levels and surface instruments. However, radar evidence of winter orographic seeding effects is normally inconclusive unless the natural IPC is very low. That is because the radar reflectivity factor is directly proportional to particle concentration, but is proportional to the sixth power of particle size. Thus, the returned signal from a few large natural snowflakes can completely mask that of an order of magnitude increase in smaller seeded crystals. Seeding could conceivably decrease the radar returned signal while increasing the precipitation rate. Therefore, radar is not suitable for detection of seeding effects except in special cases such as reported by Hobbs et al. (1981). Nevertheless, radar can be very valuable in those cases with negligible natural snow, and can provide additional information discussed below.

4.4 Some Final General Considerations

Even with a single seedline, natural variability can mask seeding effects. It is very important to not only monitor the temporal changes at a target site, but spatial changes as well. This is best done by operating some surface measurement stations in addition to the target. Such stations should be located crosswind of the area to be affected by seeding so as to provide a record of natural variations with time. Radar scanning can be very valuable in monitoring natural variations in cloud structure over the entire region of the target. Such variations can mask, or be mistaken for, real seeding signatures and it is important that they be documented. It is essential that enough observations be collected in both space and time to determine which perturbations are real seeding effects, which are simply natural variations, and which may be seeding effects masked by natural variations.

Some of the past studies reviewed attempted to "piggy-back" physical experiments on what were basically statistical designs. This was generally unsatisfactory. Most statistical experiments attempt to affect a sizeable area for a significant time requiring seeding of a relatively large volume of atmosphere; for example, the release of several seedlines for airborne seeding. Such seeding takes substantial time. Yet, one of the main approaches for analyzing physical experiments is to examine temporal changes in expected characteristics (IPC, precipitation rate, degree of riming, etc.). This is best done by minimizing the time

required for seeding; for example, to a single seedline for airborne seeding, so as to reduce the changes of large natural changes in the constantly varying atmosphere during the course of the experiment.

Some past weather modification experiments seriously underestimated the resources required to analyze their field observations, or delayed detailed analysis until several field seasons were completed. In either case very valuable feedback was lost from analysis to improving field design. In the worst case, programs were canceled after several years of expensive data collection, but before adequate analysis and reporting. Such programs were very wasteful of time and resources. It is strongly recommended that any future experiments in the Sevier Basin provide substantial funding for analysis, and that analyses of each field season's data be reasonably complete before finalization of the next season's design plan. One approach to accomplishing this is to conduct field expeditions every second or third year with the intervening time used for analysis. In general, it is preferred to have the same scientists involved in both collection and analysis of the data. This helps insure careful observations and, even more important, expands the scientists' comprehension of the overall project which can significantly improve both design and analysis.

5. SELECTION OF AN EXPERIMENTAL AREA IN THE SEVIER RIVER BASIN

The first requirement for an experimental area is that the region be at high elevation and provide significant uplift to the prevailing westerly flow during storms. Mountain ranges provide the additional production of SLW that results in snowpack accumulation throughout the winter.

Most mountains exist in the eastern portion of the basin as seen on figure 5-1 which is a landform map taken from Ralls et al. (1991). Going from south to north the major barriers include the Paunsaugunt and Markagunt Plateaus, the north end of the Escalante Mountains, the Aquarius and Sevier Plateaus, the Tushar Mountains, the Pavant Range, the San Pitch and Canyon Mountains and the Wasatch Plateau.

5.1 Transferability of Experimental Results

The Sevier Drainage is small enough that the results of experiments on any suitable mountain barrier should be readily transferable to all other barriers in the basin. Thus, the main factors in selecting the most suitable experimental area are minimization of logistic difficulties, especially related to aircraft sampling and high altitude surface measurements, and maximization of storm events for study. The fact that most of the mountain barriers form the divide between the Sevier and other drainage basins is not a concern. The primary purpose of the proposed cloud seeding experiments is to develop and validate the technology, not to produce additional water in the Sevier Basin. Once an acceptable technology has been documented, it can be applied throughout the basin to increase water supplies. Of course, successful seeding of the mountains that form the divide with other basins would result in additional snowfall in the adjoining basins because targeting cannot be confined to just one side of a mountain range. But with the semiarid nature of the entire region additional water likely would be welcomed in neighboring drainages.

5.2 Snowpack and Water Yields Across the Sevier Basin

The average annual water yield from runoff in the Sevier Basin is shown on figure 5-2 taken from Ralls et al. (1991) who in turn extracted it from the *Hydrologic Atlas of Utah* published in 1968. This figure gives an overall portrayal of the high runoff production zones which are essentially the high elevation zones. Since annual runoff is strongly related to the seasonal snowpack, with snowpack water equivalent data routinely used to forecast streamflow, figure 5-2 indicates the high snowpack areas. The highest runoff (and snowpack) regions are in the southwest corner of the eastern portion of the drainage, just northwest of Navajo Lake (the Cedar Breaks National Monument vicinity), and along the northeastern rim of the basin, on the Wasatch Plateau. Average annual yields of 20 in are indicated in both areas. The Tushar Mountains are close behind with a region producing 18 in of runoff. All other mountain areas produce considerably less runoff with 12-in maximums.

The strong relationship between runoff yield and elevation can be seen indirectly in figure 5-3 which is a logarithmic plot from all streamflow gauge data in the Sevier Basin published by Ralls et al. (1991). The yield per area is much greater for those gauges that monitor small drainage areas; that is, the unregulated high elevation headwater regions. Yield per area decreases rapidly as measurements are taken further downstream and more lower elevation terrain with regulated flows is included. A power function of the form RUNOFF YIELD = 2055 X (DRAINAGE AREA)$^{-0.47}$ provided a good fit to the data of figure 5-3, resulting in a correlation coefficient of 0.93.

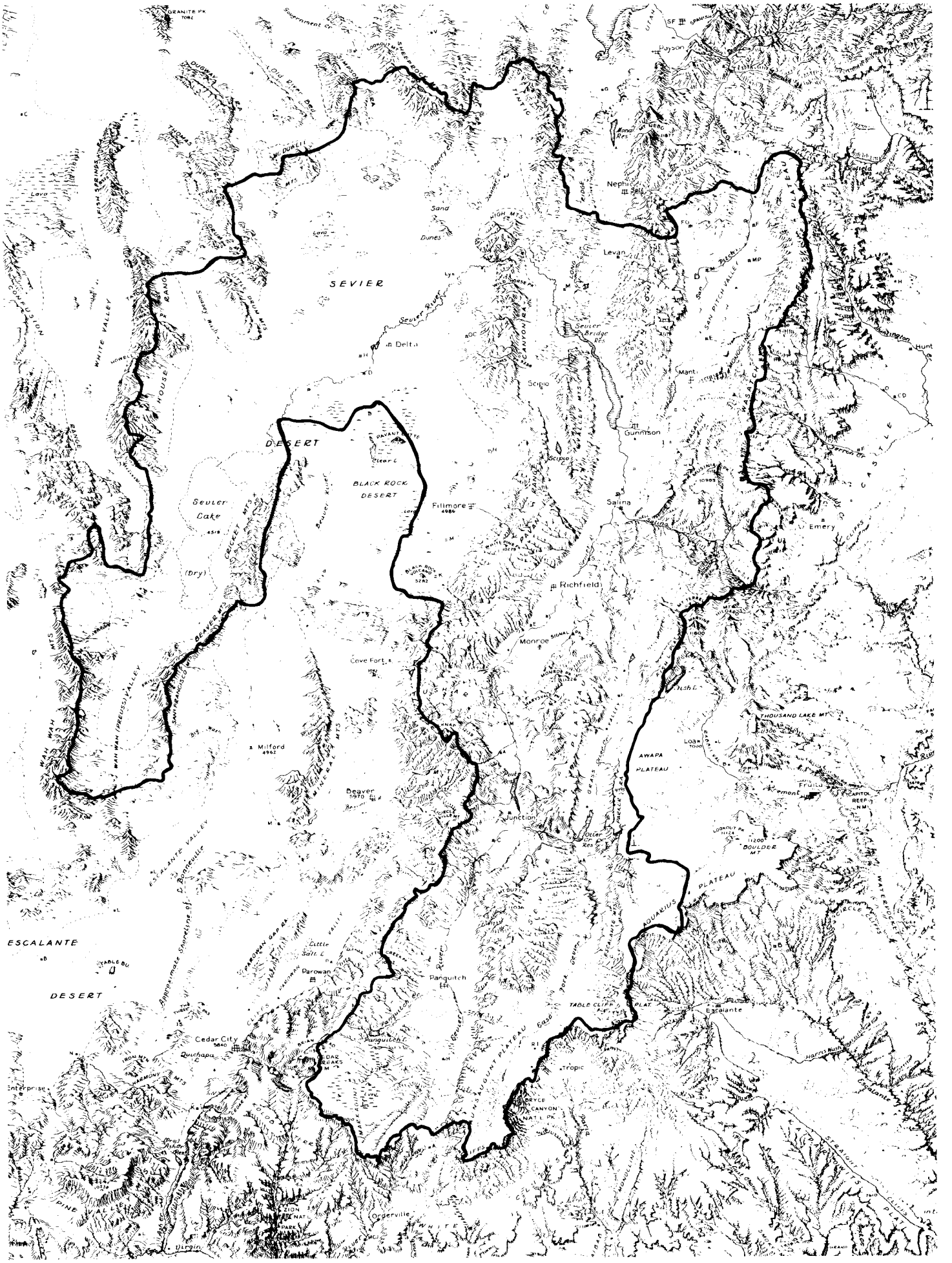

Figure 5-1. - Landforms of the Sevier River Drainage in proportional relief (from Merrill K. Ridd).

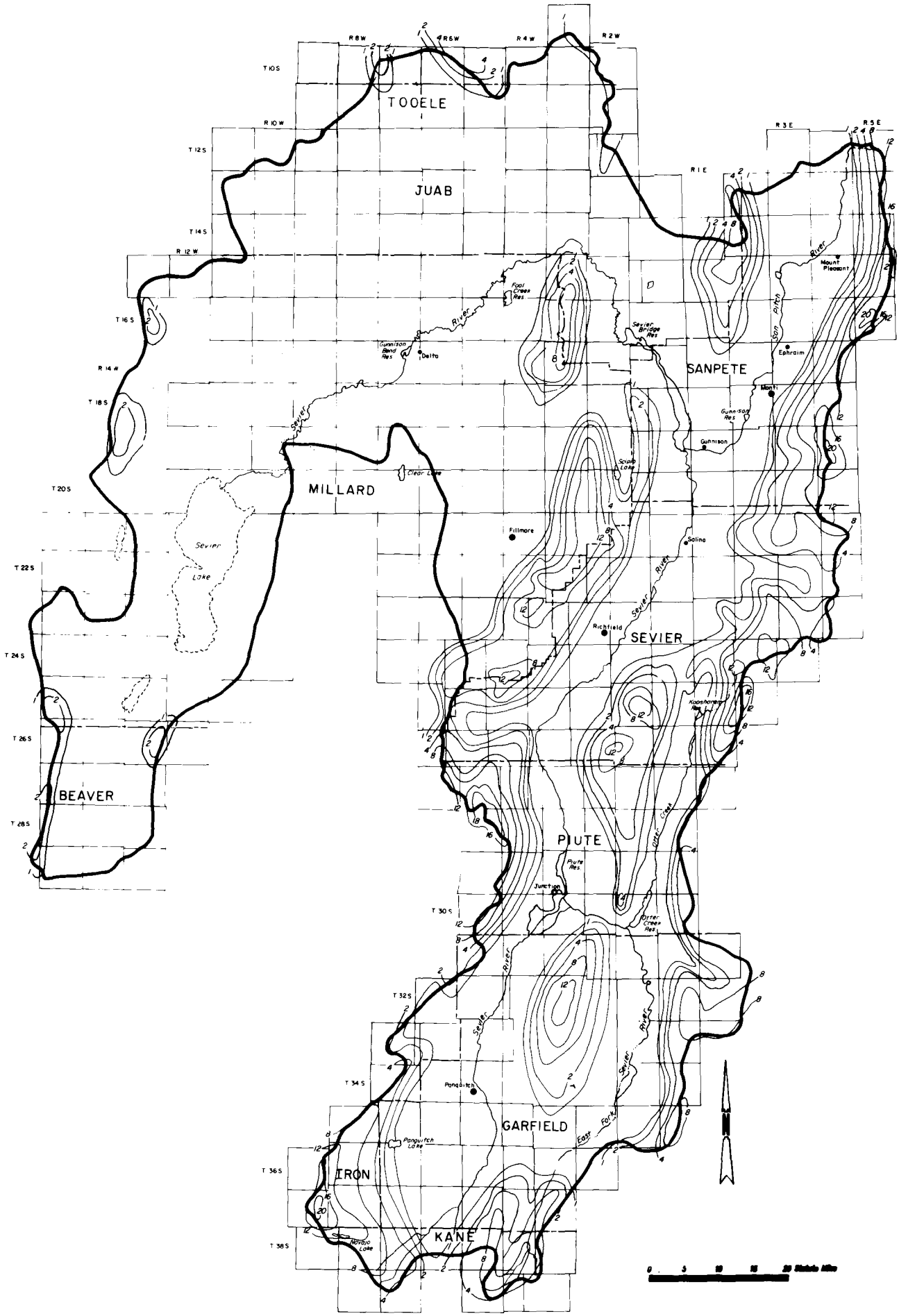

Figure 5-2. - Average annual water yield (in) in the Sevier River Basin (from the *Hydrologic Atlas of Utah*, Utah State University and Utah DWR, 1968).

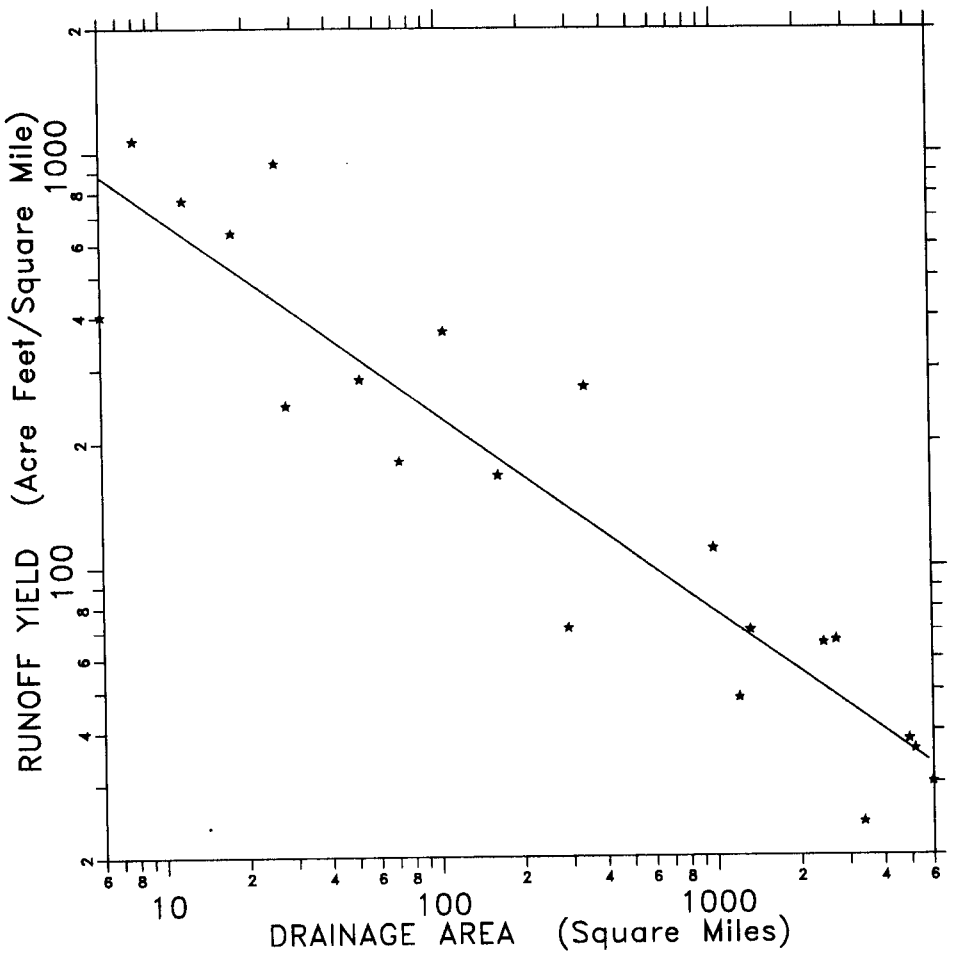

Figure 5-3. - Logarithmic plot of runoff yield vs. drainage area for selected gauging stations in the Sevier River Drainage. The power function shown, Runoff Yield = 2055 X (drainage area)$^{-0.47}$, has a correlation coefficient of 0.93.

5.3 Logistics and Other Considerations

Research programs for the Utah/NOAA cooperative program were conducted in the Tushars during several winters in the 1980's. More recent experimentation has been conducted on the Wasatch Plateau. Logistical considerations provided the motivation for moving to the new experimental area. While the Tushars were a good site for SLW investigations by microwave radiometer and some other studies, the ruggedness of the barrier prevented low-level aircraft sampling which is needed for tracking seeded zones. Further, the lack of an all-weather highway to the crestline prevented surface sampling on top of the barrier.

The Wasatch Plateau is relatively flat and in-cloud aircraft sampling to within 1,000 ft (300 m) of the terrain was proved practical during the early 1991 field season. An all-weather highway goes from Fairview to the top of the plateau at which point the highway branches into two roads (Highways 31 and 264), both of which completely cross the plateau. Highway 31 parallels the upwind edge for about 5 miles which proved highly valuable for surface sampling with truck-mounted instrumentation during the 1991 field effort. A mountain observatory was successfully operated throughout several storm periods next to the Utah DOT (Department of Transportation) snowplow shed on top the plateau. In general, the Wasatch Plateau has proven to be an excellent area for winter field research into cloud seeding.

A major positive factor for the Wasatch Plateau is that the Utah/NOAA Cooperative Program plans to continue to operate there. The Utah/NOAA Program "piggy-backs" research onto the existing operational seeding program with the T&D of ground-released AgI being the current main emphasis. The Utah/NOAA Program does not have sufficient resources to carry out demonstration program described in sections 6 and 7. But it would be far more efficient and cost effective to combine facilities and even goals then to attempt to operate two separate experimental areas.

The Cedar Breaks region also has all-weather highways with Highway 143 following the upwind edge of the plateau for about 8 miles, most of which is in the Cedar Break National Monument. The logistics of this region also should be very good. However, there are three actual or potential drawbacks to the region as compared with the Wasatch Plateau. First, storm frequency is likely somewhat less as the Cedar Breaks region is about 135 miles further south. Figure 3-10 indicated a tendency for snowpack to decrease from north to south in the Sevier Basin. That must result from more frequent storm passages, or more snowfall per storm, or both, as one moves northward. Second, and more serious, the presence of the National Monument and the Ashdown Gorge Wilderness Area, both along the westerly portion of the region, would likely preclude operation of key equipment. While seeding generators could be located on a plateau to the southwest, it would be desirable to release seeding materials and operate other instrumentation to the west as well. Third, the Wasatch Plateau is a long north-south barrier that might be suitable for the highly efficient randomized crossover design in future seeding experimentation.

An advantage of the Cedar Breaks region is that any water produced during the experimental phases would drain into the headwaters of the Sevier River. Water produced by seeding on the Wasatch Plateau would partially drain into the Sevier Drainage but most would be expected to drain into the Colorado River. It is again emphasized that the main purpose of the proposed demonstration program is to validate and improve the technology of cloud seeding for later operation application in the region.

When all important factors are considered the Wasatch Plateau appears to be the optimum area for cloud seeding research in the Sevier River Basin. Accordingly, a demonstration program was designed for that area as described in the following two sections.

6. DESIGN OF PHYSICAL CLOUD SEEDING EXPERIMENTS FOR THE WASATCH PLATEAU

6.1 Introduction

Demonstration of a validated weather modification technology to enhance water supplies in the Sevier River Basin should be pursued in a two phase program. The first should be a "physical phase" followed by the second "statistical/physical phase", discussed in section 7. The purpose of the physical phase is to increase physical understanding of the important processes in winter clouds, and how they are affected by seeding. Seeding would be confined to short-term (few hour) experiments aimed at producing measurable effects on clouds and snowfall over a limited but well-instrumented target area.

Comprehensive physical experiments monitor the most important links in the chain of physical events following seeding. Such links include documentation that the seeding agent was reliably released, that the seeding agent was transported and dispersed into the SLW zone, that ice particles were created by the seeding material, and that artificially created ice crystals grew with time and settled to the surface as snow. Comprehensive physical experiments have been made increasingly practical by recently developed instrumentation. Reclamation scientists have participated in such experiments starting with the HIPLEX summer program in the late 1970's and, during the 1980's, in winter projects in California, Colorado, and Montana. While some of these experiments strongly indicated increased precipitation, others failed to do so, at least at the intended point target. In the latter cases, it often was possible to determine plausible reasons for the apparent failure because of the comprehensive nature of the observations. That led to improved understanding and better experimental design.

In addition to the comprehensive physical experiments, a series of physical experiments with more limited objectives would investigate specific processes. One example of a more limited physical experiment is investigation of the T&D of seeding agents. This can be accomplished with an instrumented aircraft and limited supporting observations (e.g., rawinsonde data). Some T&D experiments can be conducted when full storm conditions do not exist, while the cloud base is still above the terrain permitting very low-level sampling. Another example of a limited physical experiment is study of the concentration of ice particles created by release of a seeding agent under particular temperature/moisture/dispersion conditions. Again, such observations can be made primarily by an instrumented aircraft with no attempt to follow the seeding signature to the surface.

The purpose of both the comprehensive, and the more limited physical experiments is to significantly advance understanding of the physics involved in winter orographic storms. This is required before a statistical/physical randomized program can be properly designed. The purposes of the statistical/physical phase are to show that snowfall can be increased over a target area of significant size, and to quantify the multiwinter magnitude of the increase. These purposes cannot be met by comprehensive physical experiments which are limited in time and space by their intensive observational requirements. The statistical experiment would rigorously test precisely stated hypotheses, using predetermined seeding and observational criteria, and confirmatory analysis. In addition, any statistical results must be physically plausible to be considered convincing.

At the conclusion of the two phases a validated technology would exist for seeding winter clouds over the Sevier River Basin in an effective and efficient manner. The impacts of a scientifically demonstrated ability to enhance snowfall would be far reaching as the technology could be readily transferrable to other regions of Utah and the Rocky Mountains in general. The benefits and costs of conducting a properly designed operational program would be well known. Water interests would then be in a position to make

informed choices about when, where and how to seed winter clouds while attempting to optimize water resources.

6.2 Specific Experimental Area and Experience Gained

The importance of logistical considerations in the success of physical experiments cannot be overemphasized. The Wasatch Plateau east of Fairview and Mount Pleasant is most attractive for seeding experiments because all-weather highways provide ready access to the top of the plateau. As shown on figure 6-1, the highway which runs south of the DOT snowplow shed follows the upwind edge of the plateau for 5 miles. This offers an almost unique opportunity for surface sampling through seeding plumes released on the windward slope; for example, from the high altitude seeding site shown of figure 6-1. Both truck-mounted and stationary instruments can measure the presence of the seeding material or a co-released tracer gas to determine which portion of the highway is in seeded cloud and which portions are in neighboring nonseeded cloud. The latter regions serve as "controls", documenting natural ice particle concentrations, sizes, types and snowfall rates against which the seeded ("target") zone can be compared. Simultaneously, similar observations can be made above the plateau by an aircraft flying to within 1,000 ft of the higher terrain. The ability to rapidly monitor both seeded and nearby natural cloud with aircraft and truck could provide very convincing information on the specific effects of seeding. Moreover, such information can be collected through many storms so the response of different cloud conditions can be studied.

Silver iodide (and sometimes SF_6) was released from the high altitude seeding site shown on figure 6-1 on several occasions during the 1991 field season. This seeding site was about 1,000 ft below the plateau top. The plume from this site was routinely detected with truck-mounted instruments driven back and forth along the 5 miles of that parallel the west edge of the plateau (hereafter called "upwind highway"). The same plume often was detected by the aircraft sampling above the windward and lee edges of the plateau. Moreover, SLW frequently existed during these plume sampling missions. Thus, there is no doubt that a seeding plume can routinely be transported and detected on and above the plateau during prevailing westerly flow. Near-surface winds were from the southwest for many hours prior to each frontal passage, transporting the high altitude plume approximately across the middle of the upwind highway segment.

Early in the 1991 season, prior to an accident that eliminated use of a truck-mounted Particle Measuring Systems 2D-C particle imaging probe for the rest of the field program, limited sampling of ice crystals was accomplished. The 2D-C probe was vane-mounted so it pointed into the resultant wind and ice particles flowed between the sampling arms in the normal manner. Sampling was too limited for conclusive results but the concept of observing both AgI and ice particles from a moving truck was proven. Similar sampling by an aircraft flying crosswind through a ground-released AgI plume provided convincing evidence of order of magnitude IPC increases and doubling of precipitation rates (Super and Heimbach, 1988). The combination of truck sampling of ice particles on the plateau and aircraft sampling above could provide irrefutable evidence of seeding effects.

The relatively flat terrain on top the plateau allows for good off-road travel by snowmobile or skies. It is therefore practical to operate instrumentation such as precipitation gauges all along the plateau top. Several gauges were maintained over the plateau during the 1991 experimental period.

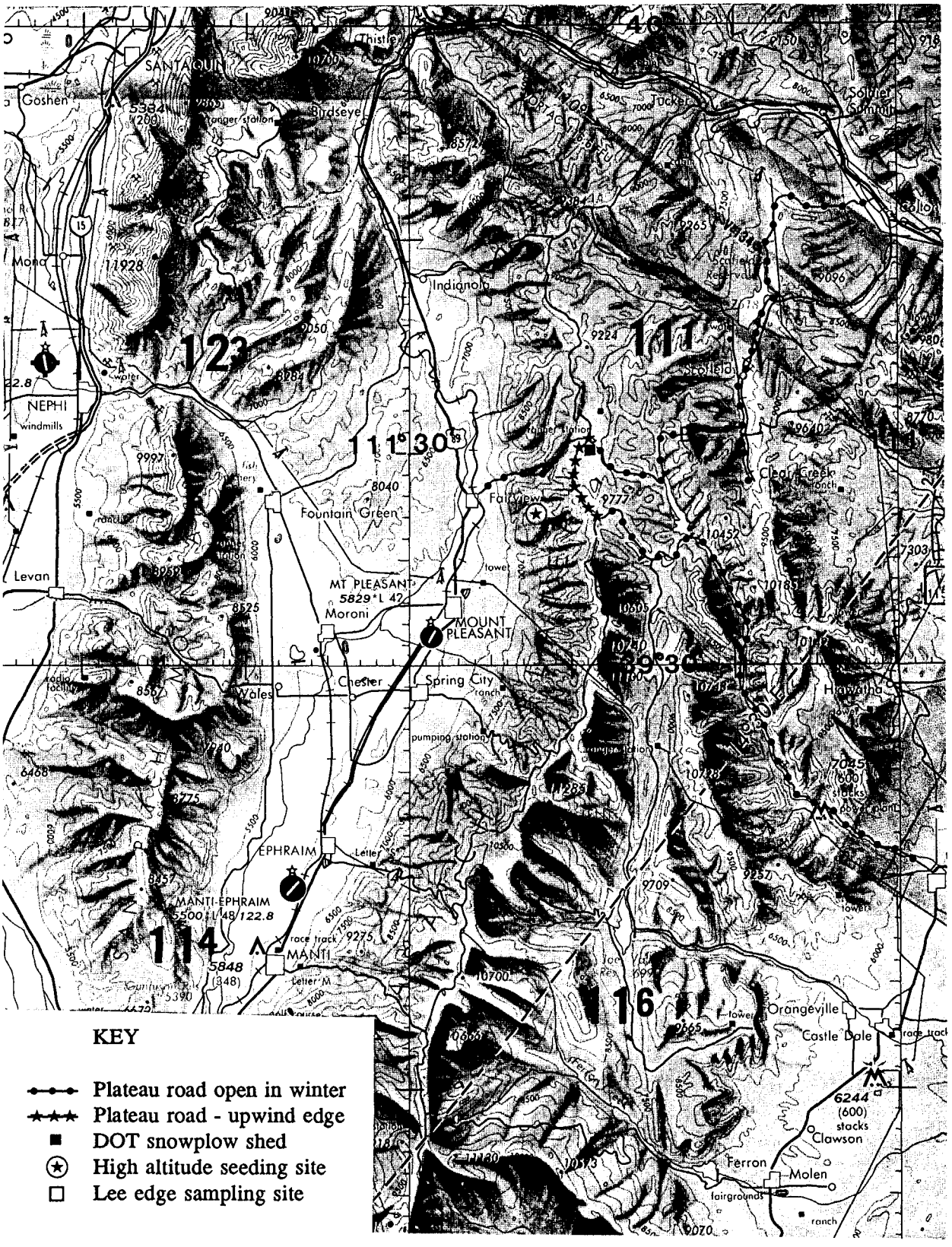

Figure 6-1. - Map of the Wasatch Plateau experimental area.

6.3 Design Specifics for Physical Experiments

Based on the 1991 sampling there is every reason to believe in-cloud observation of seeding effects can be carried out over the Wasatch Plateau with both aircraft and truck-mounted sensors. Truck sampling of the seeding agent or tracer gas, and of ice particles characteristics, should be concentrated on the upwind highway. However, with southwesterly flow, truck sampling is possible further downwind along the highway that runs from the DOT snowplow shed to the lee edge sampling site (see fig. 6.1) where radiometer observations were sometimes collected in early 1991. An aircraft can sample along predetermined flight tracks over both the upwind and downwind edges of the plateau as was done during the 1991 field program. This would provide information on ice particles at two stages in their growth and fallout and would document the seeding plume position across the entire plateau.

Three high-altitude seeding sites are recommended for physical seeding experiments to maximize the chances of the AgI crossing the upwind highway with winds between south-southwest to northwest. Only one site would be used at a time, depending upon the prevailing wind direction. This would provide a plume of 1-2-mi width above the plateau, sufficient to compare with neighboring nonseeded cloud. However, seeding sites should be tested approximately 500 ft lower than the high altitude seeding site used in early 1991. Additional time and distance would be provided for ice particle nucleation and growth if, as expected, across-the-plateau transport is usually successful from lower release sites.

Two types of seeding agent would be used, AgI and propane. The latter produces ice nucleation by cooling and high concentrations of crystals can result at temperatures as warm as 0 °C. Propane dispensers described by Reynolds (1989, 1991) would be used when it is unlikely that seeding material would mix as high as the −8 °C level. A large fraction of winter storms have most of their SLW at temperatures between 0 and −8 °C where AgI effectiveness is believed to range from none to limited. A combined seeding program using both AgI and propane may be much more effective than AgI seeding alone in the Sevier Basin. When propane seeding is done a tracer gas should be co-released so the seeded zone can be monitored.

Several past physical experiments have demonstrated increases in IPC in the clouds caused by seeding. The challenge of future experimentation will be to document corresponding changes in surface snowfall. Only a few past physical experiments have demonstrated snowfall enhancement at the surface following seeding. But such evidence is essential to validating the technology of winter orographic cloud seeding.

The best indication of seeding effects on snowfall will be from comparison between precipitation gauges within the seeded zone and outside it. High resolution gauges will be maintained along two parallel lines, near the upwind and downwind edges of the plateau, respectively. It will be attempted to locate gauges at about 1-mile intervals along each line but this must be tempered by the topography and tree cover. It is very important that gauges be located in similar small sheltered clearings in the conifer forest and have wind shields in order to minimize catch errors due to wind.

Each gauge line should be long enough to provide measurements of nonseeded snow north and south of the seeding plume for common wind directions. Truck- and aircraft-mounted instruments will monitor the AgI plume position during seeding experiments and this information will be used to estimate which precipitation gauges were within the seeded zone and which were crosswind of it. As some plume meandering can be expected, gauges near the boundary of the AgI plume may be under it at times and crosswind of it at other times. Thus, a "buffer zone" will need to be established in which the duration of seeding is questionable. Another reason for a buffer zone will be to handle errors in estimating the actual seeded region that are related to vertical wind shear. Measurements of the vertical wind structure will be

made above the plateau (Doppler acoustic sounder or profiler), but some estimation errors will still exist. Silver-in-snow concentrations sometimes will be measured at each gauge site to test the estimation method for deciding whether particular gauges were seeded or not.

Relatively high relationships can be expected during nonseeded periods between target gauges along the center (target) portion of each line, and control gauges near the north and south ends of each line. The terrain is reasonably uniform and the distance along each gauge line will be limited (about 6 miles along the windward edge and about 15 miles along the lee edge line). Relationships established during nonseeded periods with similar meteorological conditions will be used to estimate precipitation at target gauges during physical seeding experiments. Any significant differences from that predicted will be considered due to the seeding.

Many nonseeded periods used to establish target-control gauge relationships will be from nighttime when safely considerations preclude low-level aircraft flight. While daytime in-cloud flight also relies on aircraft instruments, emergency landing is much safer during daylight.

Conventional weighing precipitation gauges, modified with orifices providing 5 times the area of 8-in diameter gauges, have been successfully used on the Grand Mesa of Colorado and the Mogollon Rim of Arizona. They provided a resolution of about 0.002 in (0.05 mm), and, with daily rotation gears, a time resolution of about 5 min. Both should be adequate when seeding produces significant snowfall so similar gauges will be used on the Wasatch Plateau to monitor physical seeding experiments.

The duration of a physical seeding experiment is partially determined by the temporal stability of the atmosphere and partially by the practical flight duration of an instrumented aircraft. The latter is about 3 hours on-station time. Thus, a typical seeding experiment will release AgI for about 2 hours, commencing shortly before arrival of the sampling aircraft. The aircraft will continue to sample after generator turnoff to document changes in cloud microphysics as the concentration of seeding material decreases with time. This approach, used by Super and Heimbach (1988), can provide convincing evidence of changes due to seeding in both space and time.

It is important that measurements be made to monitor natural temporal changes in cloud conditions that are unaffected by seeding. These observations help correctly identify both natural and seeding-caused changes in IPC, precipitation rate, etc. Of course, the purpose of the control gauges is to monitor natural changes in snowfall with time. However, radar coverage of the experimental area also can be helpful by documenting the passage of any mesoscale features (e.g., "precipitation bands") during the course of an experiment.

Monitoring available SLW is very important because its presence is necessary for cloud seeding to be effective. A physical seeding experiment would not commence unless SLW were present. Moreover, any natural changes in SLW during the course of an experiment should be known for proper interpretation of results. A zenith-pointing microwave radiometer should be operated on top the plateau, crosswind of the seeded zone, to provide a time history of SLW amount throughout each experiment. If a second radiometer were available, it should be located in the seeded zone as often as practical to search for reductions in SLW caused by seeding. A truck-mounted radiometer, such as used in the 1991 field effort, could be driven back and forth along the upwind highway to sample both natural and seeded cloud. Effective seeding should reduce the SLW in the seeded zone.

It is estimated that about three winter field programs, each 4 to 5 months long, would be required for the physical experiment phase. Analyses of the many experiments conducted during that time should provide

convincing evidence concerning the conditions under which cloud seeding enhances snowfall and the conditions under which it does not, as well as the physical reasons for the different responses.

A cost estimate has not been prepared specifically for the physical experiment phase in the Sevier Basin. However, similar estimates were recently prepared for Arizona and Montana and both were approximately $2 million per year.

7. DESIGN OF A STATISTICAL/PHYSICAL EXPERIMENT FOR THE WASATCH PLATEAU

Near the end of the physical experiment phase, a randomized seeding program would be designed which, by present estimates, would require about three to four winters to conduct. While many of the specifics of the statistical/physical design must await analysis of the comprehensive physical cloud seeding experiments, several general concepts can be stated now.

7.1 General Design Considerations

The design would attempt to seed those storm conditions expected to result in enhanced snowfall according to results of physical experiments and numerical model runs. The statistical experiment would incorporate randomized seeding of either a single target area, likely with an upwind control (target-control design), or one of two target areas (crossover design). The long north-south extent and relative uniformity of terrain should make practical the crossover design (Schickedanz and Huff, 1971) for the Wasatch Plateau. The effectiveness of the crossover design increases as the correlation between the two areas increases. Even with a correlation coefficient of 0.5, the crossover can be 3 times as effective as a target-control design (Dennis, 1980). However, the crossover requires minimal contamination of the untreated area, which usually requires a buffer zone between the target areas. Observations from the physical experiment phase will indicate whether a crossover design is practical for the plateau.

Should the crossover design prove impractical a single target area would be seeded or not according to a random decision with approximately half the experimental units treated. Blocking would be used to guard against long strings of the same random decision. The use of covariates would lessen the impact of the natural variability. Covariates would allow estimation of departures (residuals) from the precipitation that would have been expected without seeding. These departures would be statistically tested similar to the approach used in the Super and Heimbach (1983) exploratory analysis of the Bridger Range Experiment, which was based on the Mielke et al. (1981) and Mielke et al. (1982) reanalysis of the Climax Experiments. Upwind and crosswind precipitation observations have been used as covariates in earlier experiments. However, improved covariates may result from combining additional routine observations such as radiometer SLW, radar cloud tops, and rawinsonde data, possibly with the aid of a numerical model. It is important to identify highly correlated covariates, that would not be affected by seeding, to maximize the power of the statistical design which minimizes the duration of the experiment.

7.2 Experimental Units

A number of past programs have used the 24 hour day as their experimental unit. However, storm conditions change dramatically in that long an interval. It is anticipated that experimental units for the new statistical experiment would be much shorter, perhaps 6 hours. The briefer units would be more homogeneous and, therefore, better represented by observations made for partitioning experimental units into similar populations. It is now recognized that a single value may only coarsely represent an entire 24 hour period (e.g., for cloud top temperature). Use of shorter units would provide the opportunity for obtaining more cases (experimental units) per winter, increasing the power of the experiment. Experimental units would be separated by a buffer period empirically determined during the physical experiment phase as long enough for the seeding agent to essentially leave the area.

The statistical design should declare experimental units by objective observations, not forecasts. In general, winter storm forecasts in mountains have modest accuracy. Their use in declaring experimental units results in many cases with unsuitable conditions, while other periods with suitable conditions are

missed. A much better approach is to continually monitor the weather and declare an experimental unit when preselected objective criteria are met for some minimum time, say 30 min. Such criteria could include radiometer-observed SLW exceeding a certain value, crestline winds greater than a speed threshold and within certain direction limits, cloud base lowering to near the mountain crest and base temperature cold enough for ice nucleation by the seeding agent. Thus, the design would attempt to exclude periods when seeding is expected to be ineffective. Some undesirable periods would still be selected for experimental units; for example, when SLW appears for awhile and then disappears. However, this objective approach based on observations would have significantly fewer "false alarms" than a scheme based on forecasts.

7.3 Physical Observations

Identical observations would be made during all seeded and nonseeded (control) experimental units for later statistical evaluation. The primary response variable likely would be total precipitation per experimental unit, averaged over all gauges in the prespecified target area. Secondary response variables might include precipitation rate and duration.

Some supporting observations would be used to partition the experimental units into meteorologically similar populations. The limits and objective procedures for partitioning would be developed prior to the randomized experiment. The most important observations likely would be seeding plume temperature and those that indicate the amount of excess SLW passing over the barrier unconverted to snowfall. This would include radiometer observed SLW, or SLW flux, in a region not affected by seeding. Measurements could be made in the buffer zone between target areas if a randomized crossover design is used. Past statistical experiments were unable to routinely monitor excess SLW availability. As a consequence, many experimental units likely were included that had no seeding potential because of lack of SLW. Inclusion of numerous units without seeding potential can seriously weaken the power of a statistical experiment.

Additional supporting observations likely to be valuable for partitioning the experimental units are indicators of natural storm efficiency of conversion of SLW to precipitation. These include measurements of the IPC, upwind or crosswind of the seeded zone, which is thought to be related to cloud top temperature. Precipitation rate observations crosswind of the target indicate the natural conversion of SLW to snowfall but do not show how much excess SLW is left for seeding to affect. A storm period producing moderate or even heavy snowfall rates may still have excess SLW available if strong winds result in substantial condensate production (Super and Holroyd, 1989). However, it is likely that most heavy precipitation rate periods result from efficient storm processes. Conversely, light snowfall periods with SLW available would tend to be inefficient. Consequently, snowfall rates observed crosswind of the target may be useful in partitioning.

Observations of key physical processes would continue to be made frequently throughout the course of the statistical program to test for flaws in both design and conduct of the experiment, and to further physical understanding. Specifically, comprehensive physical experiments and more limited physical experiments (e.g., of transport and dispersion) as described in section 6 would be continued throughout the statistical/physical experiment phase. However, it would not be practical to conduct such measurements throughout the course of each statistical experimental unit. But suitable physical measurements for a subset of the experimental units should indicate whether the seeding hypothesis was usually being satisfied.

Precipitation variables would be examined in areas outside the primary target including some gauges further downwind, both at valley locations and in the next mountain ranges in the northeast through southeast quadrant. The possibility of downwind effects (precipitation changes downwind of the intended target) due to seeding has been raised many times, but firm evidence for such effects is lacking. While most statistical suggestions indicate increased snowfall for some distance downwind of target areas, further investigation of downwind effects is warranted.

7.4 Demonstration Program Cost and Other Options

The costs of a demonstration program have not been estimated specifically for the Sevier River. Similar estimates were recently prepared for a proposed 5-year program for Arizona and 7-year program in Montana. Both estimates had an average annual cost of approximately $2.0 million, assuming 4- to 5-month field seasons. Such costs are well in excess of the current costs of the Utah operational program. It is likely that only State and Federal Governments or very large users organizations could afford the sort of demonstration program that is needed to validate the technology of winter orographic cloud seeding.

Additional costs would be required to comply with State and Federal environmental assessments. A discussion of environmental assessment and monitoring requirements is beyond the scope of this report, but compliance with these requirements obviously would be necessary.

The program that has been proposed is considered to be the best means of demonstrating a validated technology in less than a decade. However, it should be pointed out that other options certainly exist that are less costly on an annual basis. One option always is to do nothing. In this case the likely result would be continuation of operational seeding as previously conducted for modest cost. The major risk of that approach is that the program's effectiveness will continue to be unknown. However, in view of the expense of reducing uncertainties about seeding effectiveness, water users could decide to continue to accept the risks involved with operational seeding; that is, they could continue to assume that seeding was producing water worth more than their costs.

In reality, the Utah DWR has been following a much better option than "doing nothing" for over a decade in southern and central Utah. The Utah/NOAA Atmospheric Modification Program has been pursuing research into winter cloud systems and their modification as earlier reviewed. This work is ongoing on the Wasatch Plateau, located in the northeast corner of the Sevier River Basin, so it has direct relevance to the basin. An improved understanding of clouds and their modification potential has resulted, especially concerning the availability of SLW.

The Atmospheric Modification Program has recently turned its major focus toward delivery of adequate concentrations of effective ice nuclei to SLW cloud regions. Other major questions that have been identified by the Utah/NOAA program, but not yet thoroughly investigated, concern the physical processes responsible for precipitation development and the trajectories followed by seeded ice crystals.

The Utah/NOAA program funding, currently about $0.5 million per year, has restricted field programs to 6 to 8 weeks every other winter, and these programs have been able to address only one or two key questions at a time. This approach has the advantage of less annual cost than the more comprehensive program discussed in following sections. However, the current approach will require considerably longer to validate winter cloud seeding technology. Moreover, even if all key physical processes are verified, it will be difficult or impossible to accurately estimate the seasonal water increases produced by seeding without conducting a randomized statistical experiment with a strong physical emphasis. That will require funding well in excess of present levels.

The option of combining with, and augmenting, the research efforts of the Utah/NOAA Atmospheric Modification Program deserves serious consideration. With anticipated level funding for the next few years, the Utah/NOAA program plans to continue addressing the production and distribution of SLW, and the transport and dispersion of ground-released AgI. A considerable amount of sophisticated equipment will be employed in these investigations, including instrumented aircraft and surface vehicles, microwave radiometers, radar and a rawinsonde system. All of this equipment, already available to the program, would be relevant to the physical seeding experiments discussed in section 6. Consequently, even a 50-percent increase in the expected funding level of $0.5 million per year could greatly accelerate the planned research program. Such an increase would make possible the conduct of physical seeding experiments, in addition to the investigations already planned. However, field programs would still be limited to 2 months or less every other winter.

Other options could be described for greater or lesser costs per year. In general, the lower the annual cost, the longer the time required to demonstrate the technology. But there is not a 1:1 relationship between cost and time to completion as many observations and analyses can be used to address multiple questions. Thus, it is more cost effective to conduct experiments that simultaneously investigate all key processes rather than studying one or two at a time. The option discussed in section 6 and this section is believed to be the most effective approach because the benefits of cloud seeding would be demonstrated in the shortest possible time for the least total cost.

8. ESTIMATED BENEFIT-COST RATIO OF CLOUD SEEDING

As noted in section 1, one of the goals of this study is to provide reasonable estimates of the magnitude of the precipitation and resulting streamflow increases to be expected and the benefit/cost ratio of such a project. However, previous discussion has indicated that a number of uncertainties exist concerning the effectiveness of winter orographic cloud seeding. Moreover, effectiveness can be expected to vary depending upon the seeding method, storm conditions and other factors. Uncertainties about seeding effectiveness will remain until further physical studies are conducted. Nevertheless, estimates of benefit-cost ratios have been made with the caveat that they are preliminary in nature and may well be modified in the future as additional information becomes available.

A benefit-cost ratio estimate for cloud seeding basically requires knowledge of (1) the amount of additional water produced, (2) the value of the additional water, and (3) the cost of conducting an effective operational program.

Previous discussion has indicated that the current "best estimate" of additional snowfall that might be provided by cloud seeding is about 10 percent on a seasonal basis. That figure might well be increased in the future as the technology is improved and validated. However, 10 percent was chosen for the purpose of estimating benefit-cost ratios.

8.1 Modelled Augmentation of Runoff

The National Weather Service River Forecast Center in Salt Lake City estimated the additional runoff produced by the assumed 10-percent snowfall increase using their snow accumulation and ablation model. The model, described by Anderson (1973), numerically accounts for various physical processes taking place in the snowpack. The model is calibrated for a particular watershed using historical precipitation and snowpack data along with runoff measurements. The area drained by the Sevier River above Hatch, Utah, was chosen as a representative mountain watershed with adequate historical data from six weather stations in or near the area.

The calibration of the model defines six major parameters that have the largest impact on runoff predictions. One of the six, called SCF (Snowfall Catch Factor), is normally applied to precipitation data to adjust for known undermeasurements in gauge catch primarily due to wind effects. Once the model has been calibrated for a given watershed the SCF can be further adjusted to simulate changes in snowfall water content caused by seeding. It is stressed that simulated increases were applied only to snowfall, not rainfall, in the model runs.

The snow accumulation and ablation model was calibrated using water years 1952-1971. A correlation coefficient of 0.94 was calculated between observed and predicted daily streamflows for this 20-year record indicating the model provides a very good simulation of the key processes leading to streamflow. The same 20-year period was chosen to simulate seeding effects with model calculations made in six hour time steps. The procedure was to run the calibrated model with no change in SCF and then make another run with a 10-percent increase in each snowfall event. Actually, two 10-percent increase runs were made. The first assumed the same increase over the entire watershed and the second limited snowfall increases to the 60 percent of the 340-mi^2 drainage area above the 8,000-ft contour. The latter simulation was an attempt to better simulate the area actually affected by seeding. All storm periods were used in this simulation so no attempt was made to suspend "seeding" due to heavy snowpack, potential flooding conditions, etc.

Table 8.1 shows the results of these model simulation on a month-by-month basis. Percentage increases are similar for most months, near 20 percent if the entire watershed had a 10-percent snowfall increase, and about 13 percent if only the area above 8,000 ft was affected. Highest increases occur during June which is also the peak runoff month. On an annual basis the increased flows are 22 percent and 14 percent, respectively. For reference, the mean annual runoff at Hatch for the period of record was 71,324 acre-ft. Presumably the percentage increases in runoff are greater than the snowfall increases because such factors as evapotranspiration into the air and infiltration into the soil must be satisfied with or without increased snowfall. Hence, increasing the snowfall increases the efficiency of the runoff process.

Table 8.1. - Percentage increases in monthly runoff due to adjusting the snow correction factor for the Sevier River at Hatch (1951-1971).

Month	10% increase over entire watershed	10% increase above 8,000-ft contour
January	21	13
February	20	13
March	18	10
April	18	5
May	20	10
June	31	26
July	26	20
August	20	14
September	20	13
October	20	13
November	20	13
December	21	13
Annual mean increase (acre-ft)	15,923 (22%)	10,233 (14%)

Figure 8-1 shows the changes in monthly streamflows for three selected years representing dry, normal and wet conditions assuming that seeding produced a 10-percent increase in snowfall only above the 8,000-ft level. In each case most of the augmented flow occurs during May through July.

Figure 8-2 illustrates the year-by-year results of a 10-percent snowfall increase above 8,000 ft. Both augmented flows in thousands of acre-feet and the percentage increases are shown. Percentage increases range from only from about 10 to 18 percent for the water years modelled but the absolute magnitudes vary markedly from about 5,000 to over 18,000 acre-ft.

8.2 Estimated Value of the Additional Streamflow

The modelled streamflow increases discussed in section 8.1 were used by the Utah DWR as input to their Sevier River Simulation Model. Only the conservative option was modelled; that is, a 10-percent increase in precipitation above the 8,000-ft contour which resulted in an average annual streamflow increase of

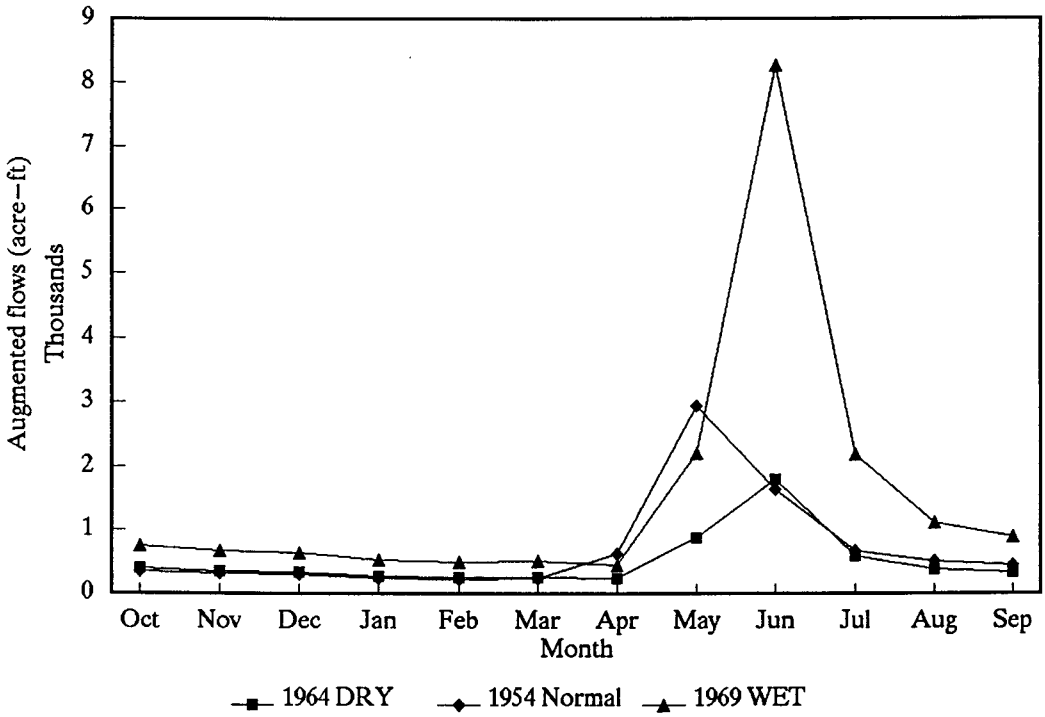

Figure 8-1. - Augmented monthly flows at Hatch, UT, assuming a 10-percent increase in snowfall above 8,000 ft m.s.l. for a dry, wet, and normal year.

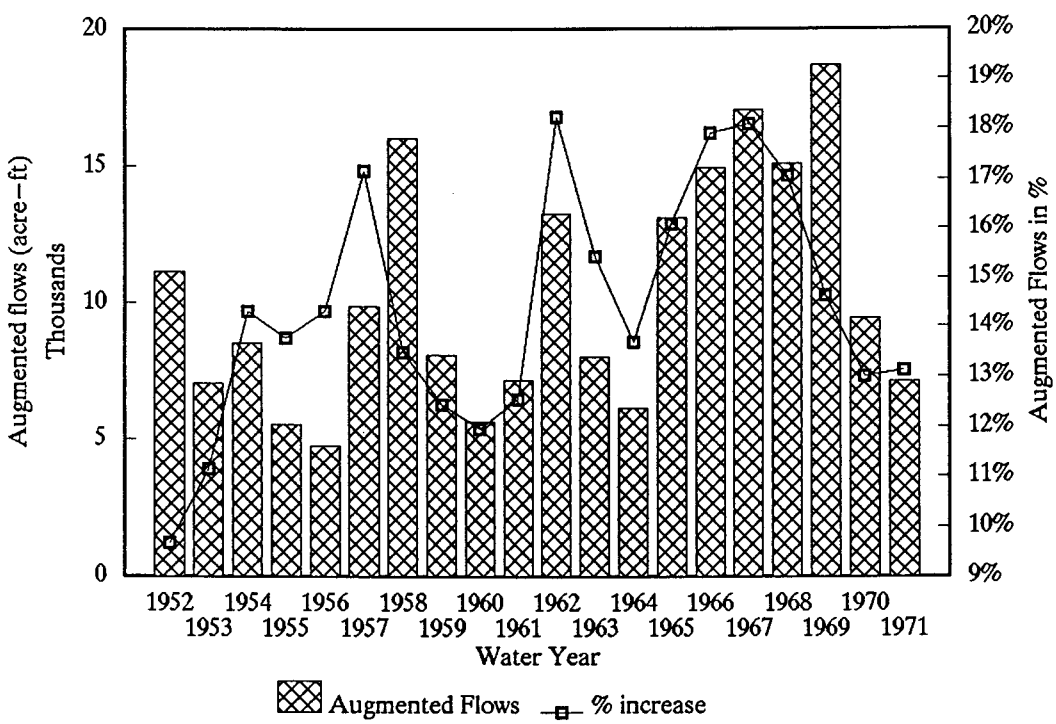

Figure 8-2. - Augmented flows at Hatch, UT, assuming a 10-percent increase in snowfall above 8,000 ft m.s.l. for water years 1952 through 1971.

10,233 acre-ft (table 8.1). Division personnel performed an economic analysis of the assumed augmented flows at Hatch, Utah, to calculate the annual benefits for several land areas along the course of the Sevier River. The net benefit for the entire drainage was estimated as $17.59 per acre-foot of water produced (Craig Miller, personal communication). While there are some uncertainties with the computerized economic analysis program, as there are with any numerical model, the $17.59 figure represents the current best estimate of the value of augmented water in the headwaters of the Sevier River Drainage.

8.3 Estimated Costs of an Operational Seeding Program

A program to evaluate the effectiveness of operational seeding has not been included in the cost estimates. Rather, it was assumed that state-of-the-art seeding methodology would be applied without serious evaluation as is normally the case for operational projects. It is well known that operational projects are difficult to evaluate statistically (see Dennis, 1980), chiefly because all "suitable" storms are seeded and none are left untreated by random decision to serve as the basis of comparison. In general, in-depth physical evaluation of seeding effectiveness is several times more costly than conducting the seeding.

Two different costs have been estimated for application of an efficient operational cloud seeding program. First, it was assumed that the present operational program in Utah is capable of producing 10-percent additional snowfall. Whether or not this is a reasonable assumption is an open question that cannot be answered without additional investigation. As discussed in section 3.1, statistical evaluations have both supported and refuted this assumption. At any rate, the current cost of the Utah operational program was estimated by considering the total cost for seeding the southern and central portions of the program which attempt to treat about 7,000 mi^2 of area above 6500 ft elevation. The fraction of this area that is the Sevier River Drainage above Hatch was about 5 percent of the total resulting in an operational cost of approximately $10,000 per season for the area above Hatch (Don Griffith, North American Weather Consultants, personal communication).

A second, higher cost for an operational program was estimated by assuming a significantly higher density of AgI generators than presently employed would be needed to produce a 10-percent snowpack enhancement, and that these generators would be located along the windward slopes rather than in valleys. Based on Holroyd et al. (1988), Super and Heimbach (1988), and similar work cited, it was assumed that generators should have outputs of about 30 grams AgI per hour vs. the 6 grams per hour in the current operational program. It was further assumed that generators should be located every 2 miles parallel to the crestline of the mountain barrier to avoid gaps between seeding plumes. Present generators are often about 10 miles apart. For the Sevier River above Hatch a 2-mile spacing would require about 15 generator sites. Radio-controlled generators would be required at an initial cost of about $10,000 each. This cost was amortized over a ten year period. It was assumed that each generator would be operated about 200 hours per season, approximately twice the rate of use of present valley generators, because high altitude generators have been shown to be effective even when a stable atmosphere traps plumes from valley generators. The additional costs of initial siting and maintenance of high elevation generators would be partially offset by not needing to pay operators at each generator site as is the current practice. Table 8.2 summarizes the main additional costs of such a program for the 28 miles of high altitude ridgeline for the Sevier River Drainage above Hatch.

Table 8.2. - Additional annual costs of an operational program using high-output, remote-controlled AgI generators with 2-mile separation.

Capital cost of 15 remote-controlled generators amortized over 10 years	$15,000
Cost of 2 percent AgI-NH_4-I-acetone @ $ 19.00 per gal. for 15 generators for 200 hours per season	28,000
Total	$43,000

Program management and forecasting costs, including monitoring of suspension criteria, should be roughly the same with either the present valley generator program or with the high altitude seeding option. The costs of manual generator rental and AgI consumption by the present program would also partially offset higher maintenance costs of high altitude generators. So, adding the $10,000 annual cost of the present program to the figures of table 8.2 indicates a total cost of about $53,000 per season for the high altitude seeding option. This is only a rough estimate. The figure could be lower if, for example, it was demonstrated that only 10 grams AgI per hour per generator provided adequate ice nuclei concentrations. The figure could be significantly (up to two times) higher if remote control generator purchase and/or maintenance is more costly than estimated, or if real-time observations of SLW presence (icing meters) and wind velocity were added to the present forecasting scheme. But the main point is that further investigation may show that a highly effective operational seeding program would be several times as costly as the present approach. That has obvious impact on benefit-cost ratios.

8.4 Estimated Range of Benefit-Cost Ratios

The value of an additional 10,233 acre-ft of runoff (table 8.1) at $17.59 value per acre-foot is $180,000 per year on the average. If that much water is being produced by the current operational program for $10,000 per season, the benefit-cost ratio is 18:1. If the much higher cost option discussed above was required to produce an additional 10-percent precipitation at a cost of $53,000 per season, the benefit-cost ratio would still be 3.4:1.

These results may be compared with the benefit-cost ratios estimated by Bowles et al. (1982) for a hypothetical drought relief program for Utah (see p. 6-10) which resulted in a ratio of 9.7:1 for a statewide program.

It appears that an operational seeding program capable of producing more precipitation in the high mountain watersheds of the Sevier River Basin would likely more than pay for itself during an average year unless (1) the costs proved to be significantly higher than those estimated, or, (2) the percentage increase in precipitation was substantially less than 10 percent. It may well be that a higher cost seeding program, using closely spaced, high altitude generators, would produce more than 10-percent additional snowfall. In that event, benefit-cost ratios would increase.

Winter cloud seeding in the mountains of the Sevier Basin appears to make economic sense if precipitation increases even approach 10 percent. Unfortunately, the reality of such an increase has not been firmly proven, although increases of that order have been suggested by some project areas in the West (American Meteorological Society, 1985). The cost of the recommended demonstration program, designed to scientifically test the reality of such suggestions, was noted in section 3.4 as approximately $2.0 million per year over a several year period.

The water user is faced with a choice. He/she can assume that suggestions of about 10-percent precipitation increases approximate reality and apply current operational seeding practices with the expectation that benefit-cost ratios will exceed (perhaps well exceed) 1.0. Or he/she can consider ways to test the reality of such suggested increases. But that requires a long-term commitment of significant resources, beyond the means of most individual water user groups. It seems likely that thorough testing of just how much additional water winter cloud seeding is capable of producing will require the cooperation of several interested groups.

9. Summary

This report has examined the feasibility of using cloud seeding to enhance the mountain snowpack in the Sevier River Basin. A review of past investigations in Utah and in nearby states indicated that winter mountain clouds often have seeding potential. Abundant SLW passes over the mountain barriers each winter unused by nature in snowfall production. On average, the seasonal amount of excess liquid water flux was roughly of the same magnitude as the annual streamflow from the mountain watersheds studied. Thus, the "raw material" needed for cloud seeding to be effective is available.

Much of the seasonal SLW flux is contained in a few large storms that are efficient in snowfall production during portions of their passage but inefficient during other stages. Additional flux exists in more modest amounts in smaller storms which are more frequent. About five to six storm passages per month are typical for the Sevier River Drainage and most will have some excess SLW.

The main SLW zone generally extends no more than 1 kilometer above the barrier crests. Ground-released AgI plumes frequently can reach much of this zone, at least using high altitude generators, and such seeding should enhance snowfall when significant ice nuclei concentrations are achieved. However, temperatures are too warm for effective nucleation with AgI during a large fraction of storms. The option of propane seeding should be considered in such conditions.

Review of the available physical evidence indicates that properly conducted cloud seeding should be capable of enhancing the snowfall in the Sevier River Basin. However, review of statistical analyses of past operational and experimental projects suggests mixed results. There is some evidence that perhaps a 10-percent increase in snowfall has been achieved by operational seeding in Utah, but conclusive proof does not exist. Firm scientific evidence concerning winter cloud seeding effectiveness is lacking in Utah and the West in general.

The main problem in converting excess SLW to snowfall appears to be adequate transport and dispersion of the seeding agent (usually AgI) and resulting ice embryos so that an ice crystal concentration of at least several per liter is achieved within the liquid cloud. The current practice in Utah operational seeding is to use widely spaced AgI generators in upwind valleys or (occasionally) near canyon mouths. There is cause for concern that this approach sometimes results in trapping of the AgI near the valley floor. On the other hand, field evidence obtained during March 1991 demonstrated that even weak convection can transport valley-released AgI into the SLW zone above the mountains. Resulting ice nuclei concentrations may be low at prevailing cloud temperatures but analyses of the 1991 data have not been completed.

Seeding agent plumes are routinely transported over mountain barriers when generators are operated well up the windward slopes. This seeding method has the disadvantages of higher cost and difficulties in targeting the windward slope unless generators can be sited on the next mountain range upwind.

A demonstration program is described for the Sevier River Basin that would place winter cloud seeding on a firm scientific footing. The recommended program would have two phases with the first emphasizing physical cause-and-effect experiments over a limited area. The most suitable experimental area is the Wasatch Plateau east of Fairview and Mount Pleasant, UT. The second phase would consist of a statistical/physical experiment to validate the multiwinter increases achievable by seeding a large area. While other options were noted that would be less costly per year, the recommended approach would have less total cost over the life of the program, and would more rapidly reach the goal of validating winter orographic cloud seeding technology.

Preliminary benefit-cost estimates are given based on an assumed 10-percent increase in snowfall with runoff calculated by a snow accumulation and ablation model. An economic analysis provided the value of the additional water. Two costs of future operational seeding were estimated. One used the costs of the present operational program and the other used significantly higher costs based on a dense network of high altitude, high output generators. The results indicate that if about 10 percent more precipitation can be produced by seeding, the benefit-cost ratio very likely will exceed 1.0, and possibly will be several times that value. It must be stressed that uncertainties exist in the benefit-cost ratio estimates, especially in estimating how much additional precipitation might be produced by seeding. That uncertainty can only be resolved by a demonstration program of the type recommended.

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