WEATHER MODIFICATION- A PILOT PROJECT

San Juan Mountains
Colorado River Basin

FINAL REPORT-FEBRUARY 1974
BUREAU OF RECLAMATION
Contract No. 14-06-D-6467

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A Pilot Project of
Weather Modification for the
San Juan Mountains of the Colorado River Basin

Final Report

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A PILOT PROJECT OF WEATHER MODIFICATION FOR THE SAN JUAN MOUNTAINS OF THE COLORADO RIVER BASIN

ABSTRACT

This is the final report on the preparation of a design program to apply results from experimental programs for augmenting orographic precipitation to a Pilot Project that would have the goal of providing ". . . sound scientific and engineering evaluation of precipitation increases over a large area by operational-type application of cloud seeding techniques. . . ",(Kahan, 1969). The report describes: (1) the purpose of the project; (2) the scientific and technological basis; (3) the design constraints; and, (4) the details of the design. The design itself includes descriptions of: (1) the experimental hypothesis; (2) the site selection; (3) the experimental procedures (randomization, etc.); (4) the data collection requirements; (5) the operations procedures; and, (6) the evaluation techniques to be employed.

DESCRIPTORS

Artificial precipitation	Snow pack
Cloud seeding	Weather modification
Orographic precipitation	Colorado River Basin
Precipitation augmentation	

P R E F A C E

This is the final report on the design study for a program of weather modification adaptation for the Colorado River Basin. It is entitled "A Pilot Project of Weather Modification for the San Juan Mountains of the Colorado River Basin".

While the publication date of this report is February 1974, the basic design was developed prior to July 1971. Most aspects of the design were completed prior to November 1970. This final report represents a summarization of reports, papers, and recommendations, mostly in written form, prepared prior to July 1971. Some publication dates shown in this report are subsequent to July 1971. These represent dates of actual publication for research carried out earlier.

The appendices to the report include: (1) published reports on certain aspects of the studies; (2) a graduate student thesis; (3) a 1969 interim report on analyses in progress; and, (4) several unpublished reports on certain aspects of the studies.

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FOR THE SAN JUAN MOUNTAINS OF SOUTHERN COLORADO

I. INTRODUCTION

A sequence of steps for developing and testing a modification technology for enhancing precipitation was adopted and described by the Bureau of Reclamation in 1966 (Bureau of Reclamation, 1966). This provided for a progression of efforts from experimental to pilot and finally to fully operational projects. The term "operational" for purposes of the planning document was used to describe projects for obtaining the benefits of an applied technology. The Colorado River Basin Act which became law in 1968, specifies the Bureau of Reclamation's obligation to develop early means of water augmentation. The sequence for the development of a precipitation enhancement technology as outlined by the Bureau of Reclamation was consistent with the recommendations of the January 1966 report of weather and climate modification by the National Academy of Science (National Academy of Sciences--National Research Council, 1966). One of that panel's recommended first steps was ". . . the early establishment of several carefully designed, randomized seeding experiments, planned in such a way as to permit the assessment of seedability of various storm types". As outlined by the Bureau of Reclamation, this type of project would represent an experimental type project. In the case of the upper Colorado River Basin, such an experimental program had been established near Climax, Colorado, by Colorado State University in 1960 with the support of the National Science Foundation. This project was as recommended by the NAS committee, a carefully designed, randomized seeding experiment, and permitted the assessment of seedability of a variety of storm types. By the spring of 1966 the Bureau of Reclamation had eight winter time orographic weather modification experiments under way throughout the mountainous areas of the western states. These were located in: (1) the Park Range in northern Colorado; (2) the Elk Mountains in southern Wyoming; (3) the Jemez Mountains of northern New Mexico; (4) the Wasatch Mountains in northern Utah; (5) the Cascade Range in Washington; (6) the central Sierra Mountains in California; (7) the Bridger Range in Montana; (8) and the Lake Tahoe area in Nevada and California. One purpose of the deliberate spread of projects was to study cloud and precipitation modification under various climatological and terrain conditions and to begin development of a seeding technology in the more critical water supply areas. Four of the eight experiments were in or immediately adjacent to the upper Colorado River Basin. Even though many questions remain unanswered, the results from such experimental programs form a solid basis for proceeding to pilot-type projects as envisioned in the operational adaptation sequence presented in the 1966 Bureau of Reclamation planning document. The potential for precipitation augmentation has been demonstrated for some areas, under certain weather conditions.

Pilot projects were envisioned as a main focus of the Skywater Program to furnish technical and environmental data and to test operational systems, procedures, and techniques evolved from prior research. The delineation of environmental problems and the determination of benefit-cost effectiveness were planned as additional key aspects of pilot projects. The work to design such a pilot project of weather modification for the Colorado River Basin was initiated in 1968. It continued concurrently with the various field programs of weather modification research during the late 1960's. It was originally intended that a pilot project would be initiated starting in the fall of 1971. Since the Colorado River Basin Act (1968) specified a final report to Congress by 1977 reporting on various reconnaissance type investigations for increasing water yields of the Colorado River Basin, the Pilot Project was actually initiated in the fall of 1970. The basic aspects of the design and the preparation for field operation were completed by that time (Grant, 1970; Grant, 1970; Bureau of Reclamation, 1970; Hurley, 1972). This report describes the design that was developed for the Colorado River Basin Pilot Project prior to its initiation.

II. PURPOSE OF THE SAN JUAN PILOT PROJECT

The purpose of the Pilot Project of weather modification for the Colorado River Basin has been stated in a number of ways. This reflects the multiple specific goals of the Project. Clearly, the overall goal of the Pilot Project is to provide a supportable basis for the Bureau of Reclamation to recommend or not recommend an operational cloud seeding program as required by the Colorado River Basin Act of 1968. Within this framework the objective includes scientific, economic, management, ecological, social, and political considerations. These are reflected in objectives that have at various times been stated in the following ways.

1. A project ". . . to add basic information to the sciences of cloud physics and weather modification, and advance technology pertinent to the operational aspects of weather modification for increasing water supplies within the Basin". (Objective as stated in the contract between the Bureau of Reclamation and Colorado State University for the preparation of the design.)

2. A project ". . . to provide sound scientific and engineering evaluation of precipitation increases over a large area by operational-type application of cloud seeding techniques employed and criteria developed through the Climax Colorado experiment. The evaluation and analyses of project data also furnish a more detailed climatology of natural precipitation occurrences over mountainous areas, improved identification of precipitation increase during different seedable conditions and its distributions over large mountain masses, and an accounting of costs involved. The Project will also afford the first major opportunity for assessing social-environmental problems associated with weather modification operations and for appraising technical performance factors".

"These objectives are oriented toward learning definite answers of the technological factors and feasibility considerations involved in producing large quantities of additional streamflow in the upper Colorado River Basin."

Studies of the associated social and environmental considerations will be made in conjunction with the Pilot Project to define any problems and suggest means of resolving them. Field experiments independent of the Pilot Project in other areas of the upper Basin and adjoining regions will furnish additional climatological data and seeding experiences to supplement the Pilot Project findings. . ." (Kahan, 1969; Bureau of Reclamation, Skywater Conference V, 1969).

3. A project ". . . to produce positive increases in snowfall over large areas of the San Juan mountains and to provide for sound scientific, engineering, and economic evaluations of the precipitation increases in technology used". (Bureau of Reclamation, 1970; Bureau of Reclamation, 1971.)

4. A project ". . . to establish, at a reasonable level of confidence, that weather modification in the Colorado River Basin can produce at least a specific amount of additional water at a cost not exceeding a specific figure. The accomplishment of this objective requires:

   1. A determination of the most likely amount of water added from a specified treatment.

   2. A determination of the cost of the treatment.

   3. A verification that a treatment deficiency at least equal to that in past experimental programs can be obtained in a full scale operational program.

(Bureau of Reclamation, 1969)

The above constitute different ways of stating the Pilot Project objectives. They all apply. Difficulties arise in accomplishing all of the objectives simultaneously. Problems related to maintaining strict scientific control while still resolving certain operational questions, introduces many difficulties. In some cases compromises are required.

III. SCIENTIFIC AND TECHNOLOGICAL BASIS FOR THE PILOT PROJECT

A. The Physical Basis for Seeding Orographic Clouds

Efforts to increase orographic precipitation were started shortly after the initial discoveries of Schaefer in 1946 (Schaefer, 1946; Schaefer and Langmuir, 1946) that clouds could be artificially modified. Shortly after the initial cloud seeding experiments, T. Bergeron (1949) made "an inventory of atmospheric clouds and cloud systems" to evaluate their potential for weather modification. He concluded that "the main possibility for causing considerable artificial rainfall might be found in certain kinds of orographic cloud systems".

Subsequent research during twenty-three years from 1946 through 1969 has shown that orographic clouds do in fact have the potential to provide one of the most available and manageable cloud sources for beneficial weather modification to increase water supplies. The greatest effort to develop this potential has been in the western United States. Commercial groups, such as power and irrigation companies took the early initiative. Analyses of these seeding programs served as the primary basis for the conclusion of the 1957 President's Advisory Panel on Weather Modification (1957) that "the most probable effect of cloud seeding operations in the mountains of the west, was a 10-15% increase in precipitation". Indications were that seeding in a number of separate projects produced an overall positive effect. For other types of clouds the indicated potential was not so clear. The conclusions of the Advisory Committee, were, however, sufficiently encouraging to stimulate increased support for research. This increased research effort, primarily supported by the Federal Government, has produced a continually improving basis for realizing the potential for obtaining additional water supplies from cloud seeding over mountainous areas. Important progress in describing and evaluating a physical basis for a usable technology has been made. Carefully controlled field tests have been conducted that show, with a high degree of confidence, positive increases in precipitation for meteorological situations during which a potential for weather modification would be expected.

The physical basis for treating cold orographic clouds by seeding was presented by Bergeron (1949) and discussed in more detail by Ludlam (1955). The orographic induced clouds along and windward of mountain ranges over the western United States, and specifically those over the headwaters of the Colorado River Basin, are frequently composed of supercooled liquid droplets. The temperature activation spectra of natural ice nuclei is such that the number of effective nuclei may not meet cloud requirements for converting the cloud water to ice formed at the warmer cloud temperatures and higher condensation rates. In such cases snow may not develop, or the precipitation process may be inefficient. If artificial ice nuclei can be supplied to an incoming saturated air stream far enough upwind of the mountain barrier, a more efficient conversion of subcooled cloud water to ice crystals should result in increased snowfall. Otherwise, the unconverted cloud water evaporates to the lee of the mountain barrier. Weather modification potential can be represented as a difference between the supply rate of condensate as the air stream is lifted over the mountain barrier and the growth rate of ice in the cloud system which consumes the liquid condensate. It can be shown under certain cloud temperature conditions that the rate of water consumption by ice crystal growth is less than the rate at which condensate becomes available to the cloud. Considerable losses of cloud water to evaporation on the lee side of the mountain barrier results under these conditions.

In other cases, ice growth by vapor deposition proceeds at a rate sufficient to use cloud water as it condenses. In some weather situations, the supply of ice crystals can be so great that particle growth is restricted by water availability and fall trajectories of the ice crystals relative to the ground may be adversely affected.

These concepts have been specifically tested (Grant and Mielke, 1967; Grant et al, 1968; Chappell, 1970; Jiusto and Holroyd, 1970 and 1971) and are demonstrated in Figure 1.

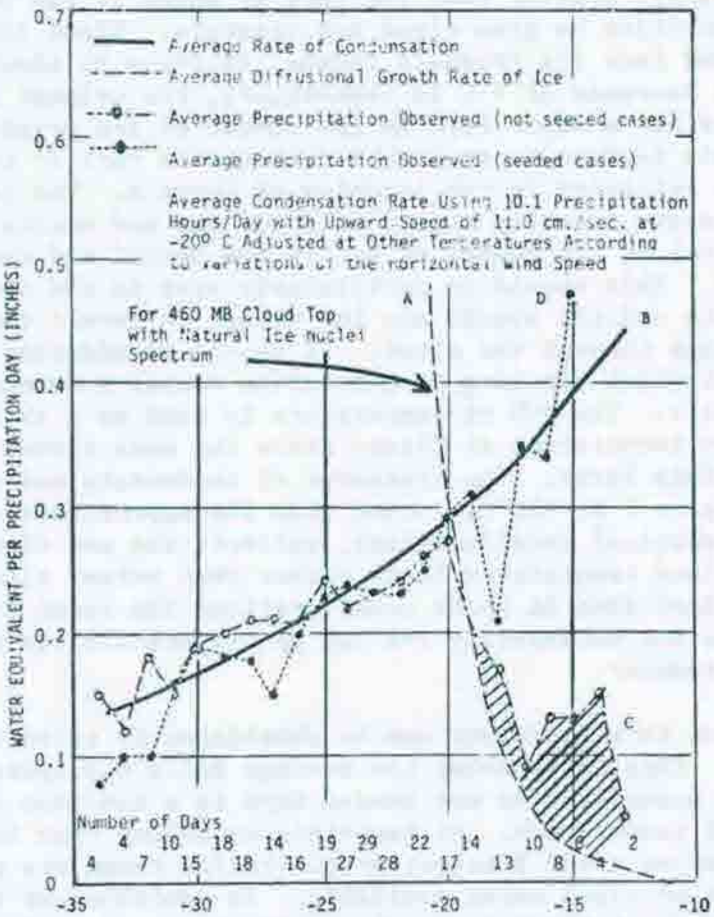


Figure 1. Distribution of non-seeded precipitation at HAO as a function of 500 mb temperature compared to a theoretical distribution computed using the mean diffusional model. Precipitation data are from Climax I sample (251) and values are a running mean over a three-degree temperature interval.

Curve A in Figure 1 shows the rate at which water can be consumed by mountain clouds with various cloud top (500 mb) temperatures assuming: (1) clouds with characteristics of those observed near Climax, Colorado; (2) ice crystal concentrations comparable to concentrations of natural ice nuclei activated at the respective temperatures, and; (3) a growth rate of individual crystals determined by Chappell (1970) based on the ice diffusional growth equations. Curve B, for comparison, shows the mean rate at which condensate becomes available for clouds with various 500 mb temperatures during non-seeded days of the Climax I experiments from 1960-1965. Note from Curve A that with increasing temperatures the potential rate of consumption of moisture by diffusional growth of the crystals rapidly decreases even though the potential condensate increases. This is due to the severe limitation in numbers of ice crystals available to consume the condensate present. Crossing of the available condensate curve and water consumption curve is nearly perpendicular. At temperatures colder than this intersection the potential to grow cloud ice is considerably greater than the rate at which condensate is formed. Conversely, at temperatures warmer than the intersection, condensate becomes available at a rate increasingly greater than the rate at which it can be utilized by vapor deposition to grow cloud ice crystals. Since ice nuclei activated, and thus ice crystals formed, increase by about an order of ten for a decrease of 4°C in temperature, the coldest cloud temperature plays a major role in the number of ice crystals present. This in turn controls the consumption rate of cloud water and is reflected in the location of Curve A. The coldest cloud temperature normally occurs at cloud top and exerts a crucial control on the number of active ice nuclei and consequently ice crystals. This should be particularly true in the orographic cloud in which updraft speeds are low enough to permit the settling of ice crystals through the cloud. It should in addition be true for <u>any</u> cloud in which settling or convection causes a downward transport of ice crystals. The 500 mb temperature is used as a reference of the cloud top temperature at Climax since the mean elevation of cloud top is near this level. The crossover of condensate and consumption curves in Figure 1 at -20°C, rather than the approximate -24°C expected from physical considerations, reflects the use of the 500 mb level as a cloud temperature index rather than actual cloud top. It is emphasized that in these considerations the cloud top temperature, and not necessarily the 500 mb temperature, is the physically important parameter.

The reality of this treatment can be considered by referring to Curve C, Figure 1. This curve shows the average daily precipitation during the Climax I experiment on not seeded days as a function of the observed 500 mb temperature. At temperatures colder than the intersection of Curves A and B actual precipitation rates are comparable to the amount of cloud water available. In contrast, at temperatures warmer than that at the intersection, the amount of condensate is considerably in excess of the natural precipitation observed at corresponding temperatures. This clearly indicates the absence of a precipitation growth process to utilize cloud condensate at a rate equal to that at which it is being formed. Efforts to describe this difference in the rate of precipitation in terms of other cloud features have not provided an explanation for this reduced precipitation rate for the warmer clouds.

The deviation of the actual precipitation curve from Curve A at near -15°C is believed to reflect a utilization of cloud water by other than the diffusional crystal growth process as computed. This might represent removal of an additional amount of condensate by accretion, ice multiplication, or by an even greater ice growth rate at these temperatures than the one calculated. In some mountain areas such a difference might even reflect a coalescence component of cloud water removal.

The hypothesis that the natural precipitation rate does in fact result from a microphysical control is supported by the observed precipitation for the randomly-selected seeded days during the Climax I experiment. Curve D shows the average precipitation on seeded days as a function of the observed 500 mb temperature. The observed precipitation for the warmer cases, as well as for the colder cases, is now in reasonable agreement with the amount of condensate available.

Similar analyses have been completed for the completely independent Climax II experiment (Chappell, 1970; Mielke, et al, 1971), which was carried out from 1965 to 1970 as a replication of the Climax I experiment, and for separate, randomized experiments in the Wolf Creek (Chappell, 1970) and Monarch Pass areas of southern Colorado. The same general features discussed above for Climax I are observed: that is, (1) a sharp drop-off in natural precipitation rates at temperatures warmer than the intersection of the condensate and consumption curves and, (2) precipitation rates for the seeded cases in reasonable agreement with expected condensation rates even at the warmer temperatures.

The above results show that under some temperature conditions considerable quantities of orographic cloud water are not used in the production of precipitation that reaches the ground during the relatively short transit time required for air parcels to move over a mountain barrier (Inefficient natural process and a potential for weather modification). Under other conditions, namely, colder cloud situations, an efficient transfer of the cloud water to precipitation particles should occur (efficient natural process and no potential for precipitation increases from weather modification). These physical processes are discussed in more detail in Appendix A, Part V, A, and in Appendix B, Parts A and B.

B. The Experimental Basis of Seeding Orographic Clouds

1. Changes in Precipitation for Specific Weather Situations

The analyses of a number of carefully designed and conducted field experiments (Climax I, Climax II, Wolf Creek, Park Range [Rhea et al, 1969]) that include randomized seeding of orographic clouds provide results that are consistent with those to be expected from physical considerations: that is, significantly greater and statistically significant amounts of precipitation occurred on seeded days with positive modification potential and little or no change in precipitation resulted on days without modification potential. Increases in precipitation exceeding 50% have been observed for experimental cases encompassing the broad range of cloud temperatures for which most weather modification potential should exist. For cloud top temperatures in the range for which the greatest potential would be expected, advantages of over 100% have been observed for the seeded days. Results of some of the preliminary analyses were reported at the Fifth Skywater Conference (Grant, L. O., 1969; Mielke, P. W., Jr., 1969; Chappell, C. F., 1969).

Tables I through IV show the results of more complete analyses of the magnitude and significance of the difference between the seeded and non-seeded precipitation for the four experiments conducted by Colorado State University. Respectively, these present comparisons in precipitation for meteorological stratifications based on 500 mb temperature, 700 mb equivalent potential temperature (700 θ_e) and 700 mb wind velocity and direction. The 700 mb equivalent potential temperature is not only an index of cloud temperature structure, but also reflects the moisture availability on an experimental day. Moreover it is independent of the assumption that cloud top is near 500 mb. Wind direction is presented only for Climax I and Climax IIB since this parameter is highly dependent on specific sites. The wind flow experimental results for the other experiments show seeding effects similar to those observed at Climax for directions that would maximize favorable orographic clouds. It can be seen from Table I

TABLE I. Ratios of seeded to non-seeded mean precipitation amounts (Wilcoxon statistic one-sided p-values: A and B for increases, C for a decrease) for 500 mb temperature partitions, °C.

	A		B		C	
	-20° to - 11°		-26° to - 21°		-39° to - 27°	
Climax I	1.85	(.206)	0.97	(.436)	0.78	(.041)
**Climax II B	1.74	(.034)(.045)*	1.28	(.230)(.350)*	1.18	(.732)(.150)*
Monarch	1.84	(.043)	1.15	(.184)	0.92	(.614)
Wolf Creek	1.90	(.093)	0.87	(.374)	1.14	(.745)

TABLE II. Ratios of seeded to non-seeded mean precipitation amounts (Wilcoxon statistic one-sided p-values: A and B for increases, C for a decrease) for 700 mb equivalent potential temperature partitions, °K.

	A		B		C	
	308 to 327		295 to 307		281 to 294	
Climax I	1.77	(.131)	0.96	(.496)	0.66	(.037)
Climax II B	1.76	(.002)(.003)*	1.16	(.764)(.750)*	1.28	(.716)(.13)*
Monarch	1.46	(.034)	1.22	(.397)	1.21	(.950)
Wolf Creek	1.35	(.015)	1.01	(.552)	0.92	(.686)

TABLE III. Ratios of seeded to non-seeded mean precipitation amounts (Wilcoxon statistic one-sided p-values: A, B, C for increases, D for decreases) for 700 mb wind velocity partitions, in meters per second.

	A		B		C		D	
	0 to 8		9 to 11		12 to 14		15 to 28	
Climax I	1.08	(.460)	1.24	(.236)	1.44	(.043)	0.73	(.093)
Climax II B	0.99	(.568)(.600)*	1.17	(.367)(.300)*	3.02	(<.001)(<.001)*	0.87	(.278)(.130)*
Wolf Creek	1.40	(<.001)	1.16	(.187)	2.21	(.001)	0.74	(.397)

TABLE IV. Ratios of seeded to non-seeded mean precipitation amounts (Wilcoxon statistic one-sided p-values: A, B, C for increases, D for decreases) for 700 mb wind direction partitions in degrees.

	A		B		C		D	
	190 to 250		260 to 300		310 to 360		10 to 180	
Climax I	1.94	(.031)	0.85	(.863)	1.41	(.095)	0.72	(.213)
Climax II B	2.27	(0.13)(.004)*	1.06	(.508)(.800)*	1.84	(.028)(.024)*	0.83	(.510)(.360)*

*Pooled p-value for Climax I and II B.

**Adjusts the sample to exclude cases of experimental contamination from upwind seeding (Mielke, et al, 1971).

and II that large positive differences in precipitation, which are generally statistically significant, occurred on the randomly-selected seeded days in the warmer temperature categories. In the colder categories, as would be expected, these advantages do not appear. In the coldest categories the seeded days generally received less precipitation, suggesting a possible decrease for those cases in which an over-abundance of natural nuclei would already be available.

Table III shows the dependence of seeding potential on the rate at which condensate is made available. It can be noted that the greatest positive advantage for the seeded days occurred with a 700 mb wind speed of from 12-14 m/sec. It is believed that one of the causes for the narrow and distinct velocity range to maximize effects was the fixed location and operation of the generators within a narrow distance range to the southwest and northwest. The failure to obtain seeding effects at the stronger wind speeds is believed to be related to the locations from which the seeding was carried out in relation to the mountain barrier. The indicated decrease at the higher velocities suggests that seeding did cause a reduction in size and fall velocity of ice crystals to the extent that in some cases precipitation, which would have reached the mountains under natural conditions, did not fall to the surface network before being carried over the mountain barrier. Generators should probably have been operated from closer distances for lighter wind speeds and clearly should have at least operated from greater distances for the stronger winds. Seeding increases may not be feasible with strong winds.

The importance of wind direction can be noted in Table IV. Airflow patterns from the southwest and from the northwest are generally normal to the complex orography at Climax and consequently produce the most marked orographic lifting.

2. Changes in Total Precipitation

An estimate of the overall change in precipitation that could be expected in the Climax area from weather modification can be made by considering changes in precipitation to be expected for each of the cloud temperature categorizations and the frequency of occurrence of those categories. This has been done by using changes in precipitation to be expected within the 308° -327°, 295° -307°, and the 281° -294° equivalent potential temperature categories for the combined Climax I and Climax IIB experimental units. The frequency of occurrence of the respective categories has been determined from the total experimental sample of 623 events. Table V shows the estimated change in precipitation at Climax for a seeded winter with normal precipitation.

TABLE V

Estimated Changes in Precipitation at Climax for a Seeded Winter Season With Normal Precipitation (≈14.00 inches)

A. All events are seeded

700 mb Equivalent Potential Temp.	Percent of Seasons Precip.	Natural Precip.	Percentage Change	Seeded Event Precipitation
308°- 327°	21%	2.94"	+70%	5.00
295°- 307°	49%	6.86"	+5%	7.20
281°- 294°	30%	4.20"	-22%	3.28
	100%	14.00		15.48"

Total Increase = 1.48" = +11%

B. Only favorable events are seeded

700 mb Equivalent Potential Temp.	Percent of Seasons Precip.	Natural Precip.	Percentage Change	Seeded Event Precipitation
308°- 327°	21%	2.94"	+70%	5.00
295°- 307°	49%	6.86"	+5%	7.20
281°- 294°	30%	4.20"	-	4.20
	100%	14.00		16.40

Total Increase = 2.40" = +17%

If all cloud events are seeded, approximately 11% more winter time precipitation should occur. When seedability criteria are considered, and seeding is conducted only when favorable events occur, the increase in precipitation from seeding should amount to about +17%. This is probably representative of the potential for precipitation increase in most of the northern and central portions of the Colorado River Basin. Nearly as much return, around +15%, could be achieved by seeding only the events within the warmest temperature category. This would require seeding only during the periods when about 21% of the natural precipitation is accumulating.

The change expected from seeding in other areas can be more or less than this depending on the relative frequency of the respective temperatures and on the precipitation efficiency of the natural clouds. These parameters can be reasonably evaluated for sites for which (1) upper air data is available for estimating the rate of formation of condensate and cloud temperature and (2) precipitation data are available for estimating the rate of natural precipitation as a function of cloud temperature. A potential overall increase in precipitation of over 30% is indicated for the San Juan areas using this type of analysis even after taking into consideration the "signature" corrections for removal of cloud water by other than vapor deposition processes. The results of the Colorado State University Wolf Creek Pass Experiment, while not specifically designed to optimize precipitation evaluation, are consistent with these interpretations.

3. Changes in Streamflow

Careful evaluation of streamflow changes caused by the seeding are not feasible for the Climax experiment since randomization was on a daily basis throughout, and all precipitation during the winter accumulates as snow which melts and runs off the following summer. Seeding carried out on an annual basis during the Colorado State University randomized experiment in the Wolf Creek Pass area provides a basis for estimates of streamflow changes associated with seeding. Figure 2 shows a comparison of seeded area streamflow with that for a control area for non-seeded (historical and randomly selected) and seeded (randomly selected) years. It can be noted that the correlation for non-seeded years is very good, r=.97, and the coefficient of variation is low, %.1. The likelihood of receiving actual streamflow observed in two of the three randomly selected seeded years is low, with p values of less than .05. The third year, while having a somewhat higher expectancy, is still low. The probability of the streamflow for the combined three seeded years equaling or exceeding the observed value by chance is very low, p = .005. The observed precipitation excess during seeded years of 18.9% (228,000 A.f.) is in reasonable agreement with the overall change in precipitation to be expected. This is particularly true since seeding was carried out for only about 3/4 of the period each winter during which precipitation accumulates to produce the summer streamflow.

4. Cloud Seeding Effects on Precipitation Intensity and Duration

An investigation into the nature of the seeding effect at Climax indicates that seeding influences the duration of precipitation more than its intensity(Appendix G). These effects can be seen in Figure 3. The pronounced effect of seeding upon precipitation duration for the warmer cloud systems suggests a threshold of cloud microstability in cold orographic clouds that must be overcome before precipitation occurs. The natural supply of ice

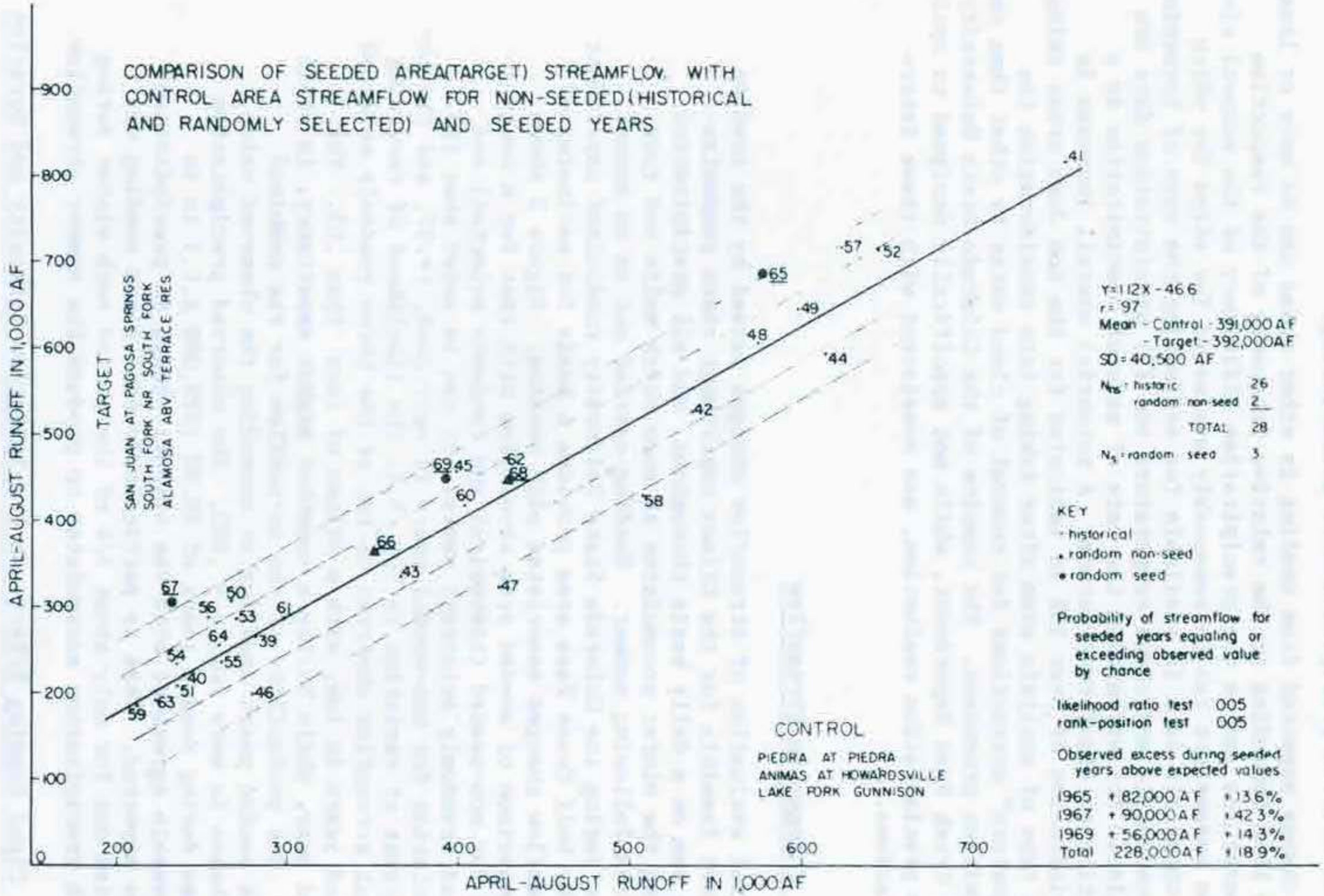

COMPARISON OF SEEDED AREA(TARGET) STREAMFLOW WITH CONTROL AREA STREAMFLOW FOR NON-SEEDED (HISTORICAL AND RANDOMLY SELECTED) AND SEEDED YEARS
TARGET
SAN JUAN AT PAGOSA SPRINGS
SOUTH FORK NR SOUTH FORK
ALAMOSA ABV TERRACE RES
APRIL-AUGUST RUNOFF IN 1,000 AF
CONTROL
PIEDRA AT PIEDRA
ANIMAS AT HOWARDSVILLE
LAKE FORK GUNNISON
APRIL-AUGUST RUNOFF IN 1,000AF
Y=1.12X - 46.6
r=.97
Mean - Control - 391,000 AF
- Target - 392,000AF
SD=40,500 AF
historic 26
random non-seed 2
TOTAL 28
random seed 3
KEY
historical
random non-seed
random seed
Probability of streamflow for seeded years equaling or exceeding observed value by chance
likelihood ratio test .005
rank-position test .005
Observed excess during seeded years above expected values
1965 +82,000 AF +13.6%
1967 +90,000 AF +42.3%
1969 +56,000 AF +14.3%
Total 228,000 AF +18.9%

Figure 2.

crystals is generally sufficient to overcome this threshold for the colder cloud systems. However, this is frequently not the case for the warmer cloud systems, and for these conditions seeding appears to overcome cloud microstability to produce precipitation for many additional hours. The results also indicate that overseeding of the coldest cloud systems (to cause a decrease in precipitation) was present and that this also is mainly a duration phenomena. The relatively small contribution to total precipitation change by the precipitation intensity change component suggests that the efficiency of the natural precipitation process is relatively high during precipitation occurrences, once the stable cloud microstructure has been disrupted.

These findings have important implications in the design of experimental and operational cloud seeding programs. They indicate that real emphasis should be placed on cloud seeding, rather than on precipitation seeding.

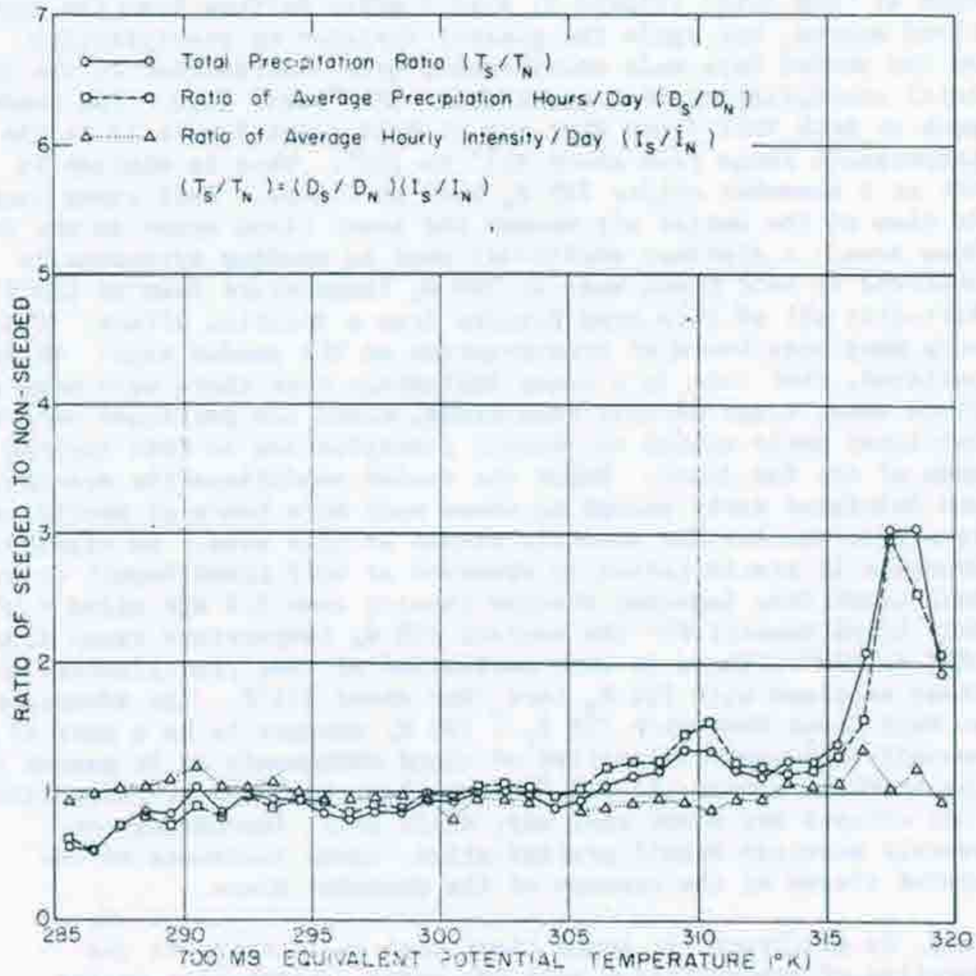


Figure 3. Seeded to non-seeded ratios of total precipitation change, precipitation duration change, and precipitation intensity change as a function of 700-mb equivalent potential temperature. Plotted values are computed using a running mean over a 5K temperature interval. Precipitation data were measured at the High Altitude Observatory during experimental days of the total Climax sample (623 days).

A similar analysis has been made for the Colorado State University Wolf Creek Pass experiment. The results are similar to those found at Climax. Figures 4 and 5 show, (for two separate precipitation stations near Wolf Creek Pass, respectively.) the seed/no seed ratios for the precipitation total, duration, and intensities as a function of 700 mb potential equivalent temperature. Figure 4 is for a station, "Wolf Creek Pass West", 4.4 miles by road (4.0 air miles) west of the summit of Wolf Creek Pass at an elevation of 9,510 ft. msl. Figure 5 is for a station "One East", 1.2 miles east (1.0 air miles) of the summit of Wolf Creek Pass at an elevation of 10,660 ft. msl. The figures are prepared in the same manner as Figure 3 for the High Altitude Observatory near Climax. The range of temperatures included covers all categories for which at least nine events occurred in both the seeded and in the not-seeded samples. It can be readily observed at the Wolf Creek West site on the upwind side of the mountain range (nearer to the cloud source) that the increase in duration of snowfall made a far greater contribution than precipitation intensity to the higher total precipitation amount that occurred on the "seeded" days. The contribution of precipitation intensity was of more overall importance at "One East" (Figure 5) some 5 miles further from the orographic cloud source, but again the greater duration of precipitation on the seeded days made considerably more contribution to the greater total precipitation that occurred on the "seed" days. The maximum peak at both Wolf Creek West and at Wolf Creek Summit is in the temperature range from about 311° to 316°. This is similar to but at a somewhat colder 700 θ_e than at Climax. This seems reasonable in view of the wetter air masses and lower cloud bases in the San Juan area. A distinct additional peak in seeding advantage is observed at Wolf Creek West at 700 θ_e temperature down to 295°K. Virtually all of this peak results from a duration effect. There were many more hours of precipitation on the seeded days. It is believed, that this is a clear indication that there were many situations when, under natural conditions, cloud ice particles were not initiated early enough to produce precipitation in this upslope area of the San Juans. Under the seeded conditions the precipitation was initiated early enough to cause many more hours of precipitation that reached the mountain slopes in this area. No significant decrease in precipitation is observed at Wolf Creek Summit or at Wolf Creek East (another station located some 5.0 air miles E of Wolf Creek Summit) for the overall 700 θ_e temperature range from 295° to 310°. There is some indication of less precipitation at these stations with 700 θ_e less than about 301°K. The advantage at Wolf Creek West with 700 $\theta_e \geq 295$ K, appears to be a part of an overall increased utilization of cloud condensate as it passes over the mountain range. At 700 θ_e less than about 301 K, redistribution effects may occur that may, while still increasing the overall mountain massif precipitation, cause increases on the upwind slopes at the expense of the downwind slope.

Thus, as at Climax, it seems clear that an increase in the duration of precipitation made the major contribution to the increase in precipitation on "seeded" days during Wolf Creek Pass experiments. At the warmest temperatures an intensity effect appears, however, to be making more of a contribution than at Climax.

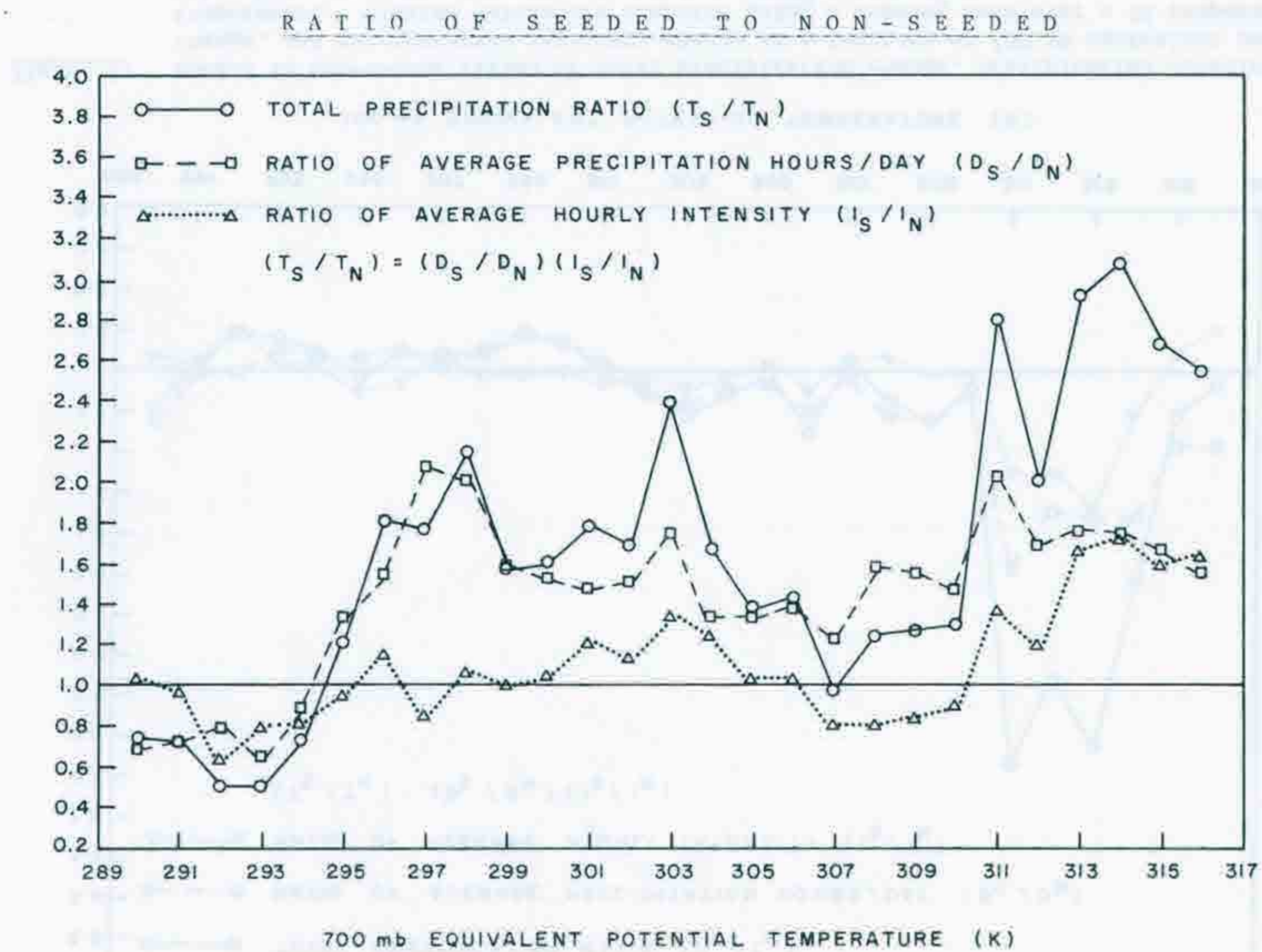


Figure 4. Seeded to non-seeded ratios of total precipitation change, precipitation duration change, and precipitation intensity change as a function of 700-mb equivalent potential temperature. Plotted values are computed using a running mean over a 5K temperature interval. The mid-point temperature is plotted. Precipitation data were measured at Wolf Creek West.

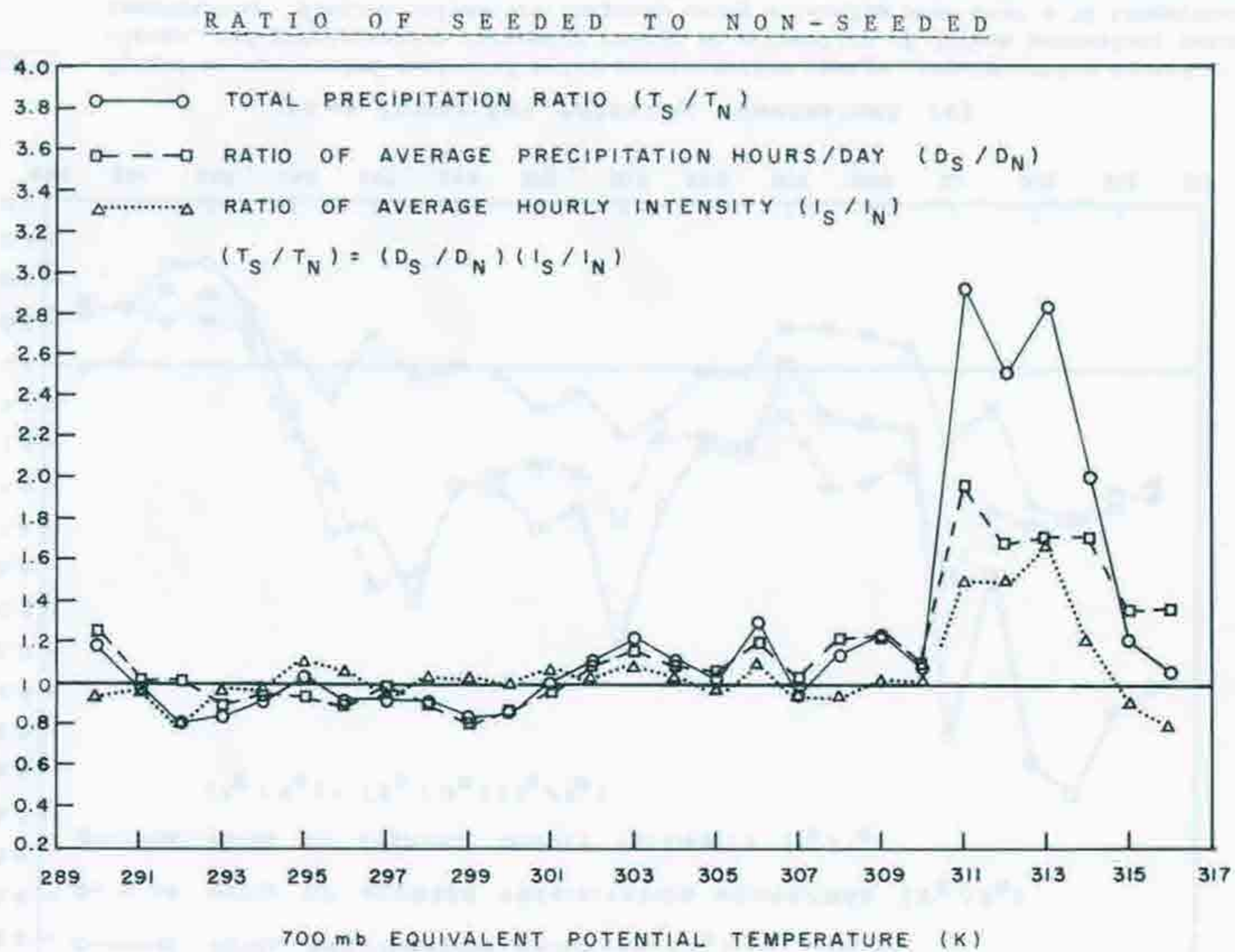


Figure 5. Seeded to non-seeded ratios of total precipitation change, precipitation duration change, and precipitation intensity change as a function of 700 mb equivalent potential temperature. Plotted values are computed using a running mean over a 5K temperature interval. Precipitation data were measured at Wolf Creek Summit.

C. Economic Considerations

Concern and controversy over the availability and quality of the limited streamflow from the mountains of the Colorado River Basin are as serious as any in the nation. Preliminary studies indicate that some 2 million acre feet of water might be added annually to the Colorado River by cloud seeding (Crow, 1967; Grant, 1967; Hurley, 1968). Rudel et al (1973), as part of this study, have compared weather modification with other proposed means of augmenting water supply, and reached the following conclusions:

1. The benefit/cost ratio varies depending on the place of water use. The water which is used in Arizona has a tentative benefit/cost ratio of 13.1 to 1, that used in New Mexico of 16.3 to 1, and that used in California a ratio of 21.3 to 1.

2. Compared with other proposed means of augmenting water supplies, weather modification appears to be one of the "least cost" alternatives. It is shown to have direct costs of \$0.91 to \$1.15 per acre foot of water produced. Indirect costs of additional snow removal and the loss of personal income due to mine closing adds \$0.15 to \$0.19 per acre foot. Extra market costs such as traffic delays caused by additional snow on the Continental Divide would increase costs somewhat, about \$0.15.

3. A very low proportion of weather modification costs, 12.4 percent, is for capital construction. Thus, the program is easily reversible with little loss of sunk costs.

4. Variable costs of operation are but \$975 per day. Thus, a relatively small increase in daily precipitation, 80 acre feet, would cover the direct costs of operation. This is important in making daily operating decisions concerning go or no-go.

5. Water produced by weather modification is valued at \$2 per acre foot for power production and at \$14.50 to \$26.50 per acre foot for irrigation of forage crops. In the long run, if the additional water is used for higher valued fruit and vegetable production, or for domestic and industrial purposes, its value would rise sharply.

6. Extra-market values related to weather modification could include travel delays, grazing and timber re-scheduling, and health effects, changes in plant and animal communities, and other possible spillover effects. Preliminary investigation of these factors suggests that, while they have little effect on the total costs of weather modification, they may be very important to individuals and groups affected. Distribution effects are important as the benefits accrue to downstream users and some of the costs are incurred by Coloradons. Adversely affected groups have been responsible for prohibiting the progress of weather modification projects when their complaints have been ignored in the planning phase. From these experiences, it is clear that extra-market effects are

not unimportant even though they may be a small proportion of total costs. There is a need for further research on the long-run economic effects of weather modification programs on extra-market factors.

D. Summary of Background Basis for Pilot Project

In summary, physical considerations show that potential for weather modification should exist over the Colorado River Basin during some weather situations. Field experiments to test for changes in precipitation from seeding confirm the reality of these expectations. Field experiments to evaluate changes in streamflow and preliminary economic analyses also show that changes in precipitation are reflected in increases in streamflow and that weather modification should be one of the "least cost" alternatives for increasing water supply from this basin.

IV. DESIGN CONSIDERATION

Several constraints to the Pilot Project design require careful consideration. The design must have the inherent capability of detecting 10-30 percent precipitation increases with a reasonable degree of confidence, even though natural precipitation variations among winter seasons might exceed 400%. When the larger variations in precipitation and the frequent occurrence of persistent weather patterns for extended, variable and undefined periods are considered, the requirement for randomization between "seeded" and "not seeded" events is clear. On the other hand, since the project is intended to test "an operational-type application of cloud seeding techniques", it must stress procedures employed in operational programs. Streamflow for the Colorado River Basin is primarily from mountain snows that accumulate during the winter season. In a fully operational,unrestricted seeding program, activities should be carried out any time that seeding potential exists so that seeding effects are optimized and any increment of precipitation increase is added to and stored in the mountain snow pack. This is not accomplished when seeding is carried out on a randomized schedule with a period shorter than a natural water year. The verification (scientific) and "application" requirements thus are not mutually supportive. Further, when public issues are considered, such projects must be restricted when danger or damage might result. This restraint affects both the "scientific" and "application" aspects of a field program.

Two distinct experimental designs have been considered. The first of these two designs places emphasis on changes in snowpack runoff relationships between two highly correlated regions. The experimental seeding units associated with this first type of design is the winter time precipitation period (about November 1 through April 30 of the following year). This interval corresponds to the natural snowpack accumulation period that provides water for the runoff during the following spring and summer. This design allows project operations to simulate application-type programs. It also provides refined estimates of cost effectiveness. It places emphasis on evaluation in terms of water yield. Evaluations of precipitation differences between seeded and not seeded events can also be made, but with less confidence than when randomization is among the respective precipitation events. This type of experiment provides the most informative design choice if two well correlated areas can be seeded without contaminating each other. When historical data is available, it can, with adjustments, be useful (Wu et al, 1972).

The other type of design places emphasis on changes in precipitation. A 24-hour experimental unit can be used so that a large number of randomly selected seeded and not seeded experimental units can be obtained for subsequent analysis. The 24-hour unit has the advantage of (1) being long enough so that any contamination at the time boundaries between the seed and not seed events may represent a relatively small portion of the total episode and (2) being short enough to provide reasonable homogeneity in meteorological conditions and seeding potential. This type of design maximizes the opportunity to identify meteorological conditions associated with seeding success and has been used with success in previously conducted winter time orographic seeding studies such as those carried out at Climax. This type of design has severe limitations in making direct evaluations of streamflow changes, since a series of one day seeding episodes are interspersed during the snow accumulation season. The seeding contribution to the streamflow is reduced since a large number of events with modification potential are not seeded. Only 20-50 percent of precipitation events in the Colorado River Basin have modification potential. When a randomization procedure leaves a portion of these events unseeded, the number of events seeded and contributing to the annual streamflow is seriously reduced. Restrictions to seeding during avalanche and heavy snow episodes, etc., further reduce the number of seeded events. The reduction of seeding in a given winter season can so reduce the percent change in total streamflow that evaluation of this is extremely difficult or impossible. Contamination can also be serious if carry-over effects from seeded to not seeded events occur. This type of design also requires substantial alterations in the seeding program from that in a fully application-type program.

It is clear that each of these experimental approaches has advantages and disadvantages. The Bureau of Reclamation has expressed its desire to place maximum emphasis on detecting changes in precipitation from which conversion to streamflow would be determined from historical precipitation-streamflow relationships (Kahan, 1969). Consequently, the second type of design involving randomization of individual seeding episodes is emphasized in the design that follows.

stated its objectives be could better met

V. PILOT PROJECT DESIGN

A. Cloud Seeding Hypothesis or Model

The physical concepts related to orographic precipitation and the definition of weather modification potential for the Pilot Project are those described in Section III A, "The Physical Basis for Seeding Orographic Clouds". The basic process involves an evaluation of the modification potential by comparing the rate at which cloud water is removed in relation to the rate at which cloud liquid water is being condensed as an air mass is lifted over the mountain barrier. The basic hypothesis is that seeding potential may exist if the rate at which cloud water is removed is less than the rate at which cloud water is being formed. Under these conditions cloud water is carried over the mountain barrier and re-evaporated on the lee side of the mountain. It is, therefore, lost to the precipitation process and, in terms of precipitation on the mountain barrier, precipitation efficiency is less than optimal.

The following is a brief description of the physical and seeding concepts. This is in part repetitive with the information in Section III, A, but is included in this section on "Project Design" as a statement of the cloud seeding hypothesis to be tested. As moist air is lifted over a mountain barrier, the air expands and cools. A temperature is ultimately reached which causes the amount of water vapor in the original unsaturated air volume to become saturated for the new and lower temperature. As continued cooling takes place cloud droplets condense to maintain the vapor pressure in the volume near water saturation. The original parcel temperature, humidity and upward speed, therefore, constitute major controls on the supply rate of cloud water available for the formation of precipitation. Once the cloud droplets are condensed they closely follow the airflow and, if not removed, evaporate as the air stream descends the lee of the mountain barrier. Their fall velocity and fall distance are generally negligible during the short transit time over the mountain barrier, which is seldom more, and can be considerably less, than one hour. There are always sufficient condensation nuclei present to form the individual cloud droplets. Once formed, however, small cloud droplets will remain in liquid form until temperatures are lowered to near -40°C unless certain additional ice-forming nuclei are also available. Concentrations of these ice nuclei are considerably less than the concentrations of condensation nuclei, and in many clouds there are relatively few ice crystals formed. Once ice crystals form they grow very rapidly by vapor diffusion since the vapor pressure over ice is considerably lower than that over the water drops. The vapor removed by this growth of ice is resupplied through evaporation of cloud droplets. In many cases the concentrations of ice crystals are too small to use or consume all of the cloud water. This is particularly true at warmer temperatures where natural aerosols become increasingly inefficient as ice nuclei. The concentration of natural nuclei are nearly always sufficient to utilize all cloud water for clouds with temperatures of about -25°C and colder. The deficiencies of effective ice nuclei become progressively greater with temperatures increasingly warmer than about -25°C. It is for clouds in these warmer temperature ranges that the introduction of an artificial supply of ice nuclei should increase the precipitation efficiency. Since the number of available ice nuclei decrease by roughly a factor of about 10 for each 4 to 5°C increase in temperature, the coldest temperature in the cloud does constitute a major control on cloud concentrations of ice crystals. This temperature represents an important control, therefore, on the concentrations of ice crystals that form in the cloud and, in turn, on the potential for microphysical modification. This assumes that fall velocities of crystals are sufficient for them to settle against the mean upward motion of the air flow. This is generally the case in winter time orographic clouds over the Colorado River Basin. It is not always true in convective elements.

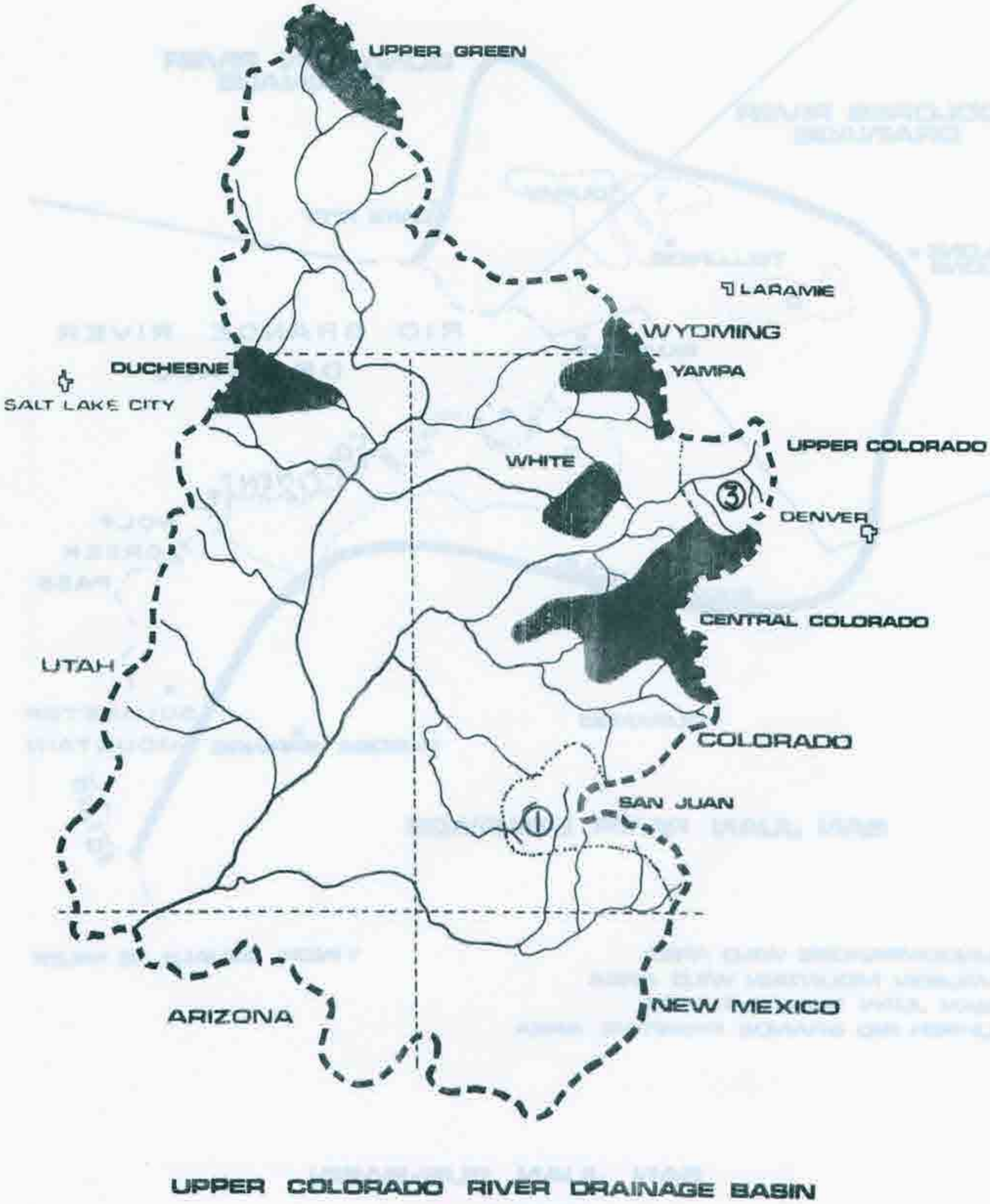
This cloud seeding concept allows for adjustments in the modification potential for processes other than growth of ice crystals by vapor diffusion. Other processes, however, are not well described, and can be considered only in a qualitative manner. These "other" processes probably (under differing conditions) include: (1) cloud water removal by accretion; (2) "Ice multiplication" that provides ice forming particles in greater numbers than generated from primary ice nuclei; and, (3) the introduction of crystals from upper cloud layers at still colder temperatures. The field studies at Climax show that cloud water removal by these processes is relatively small in the northern Colorado Rockies as represented by observations at Climax. They are more important in the San Juan area of southern Colorado. Analysis of precipitation data, studies of ice crystals, and the results of seeding experiments for this area all show that (even with an improved cloud water removal from these processes) a considerable requirement for additional ice nuclei still exists for individual cases with cloud top temperatures warmer than about -25°C.

Operations based on this concept of weather modification potential from orographic clouds require continual seeding for extended periods of time to increase cloud ice crystal concentrations to optimal levels for the utilization of cloud condensate. Primary controls for the production rate of condensate are: (1) wind direction and velocity relative to the mountain barrier, (2) temperature and thermodynamic stability of the incoming air mass, and (3) the amount of moisture in the incoming air mass. These controls frequently remain nearly constant for extended time intervals. During these extended intervals the natural or seeded microphysical processes can be repeated over and over as new air is continually lifted over the barrier. Thus, in an application-type project the operational procedures should frequently remain the same for many hours. This is critically important for seeding over the Colorado River Basin since the high topography produces many hours with low precipitation rates, even when all cloud condensate is utilized to form precipitation. Experiments at Climax and Wolf Creek Pass by Colorado State University have emphasized such continuous seeding for extended periods of time. Admittedly, there are many perturbations including precipitation from convective elements, passing convergence zones and frontal systems, and general storms, superimposed on the orographic component. While increases and/or decreases in precipitation may result from seeding these perturbations, orographic cloud seeding concepts suggested by Ludlam and tested at Climax indicate that an important component of the total precipitation, and of the seeding potential, is associated with the orographically produced clouds. A bias (advantage) for the seeded cases in the total precipitation is expected from systematic treatment of the orographic component. These orographically induced clouds generally occur in advance of, associated with, or behind the main frontal or upper air weather systems. The major role of these storm systems with respect to orographic clouds is to advect large quantities of moist air into the area. Since the seeding design is for the orographic component and, since these events last for extended periods of time, a time-averaged model for operations and evaluation is used. This provides the possibility of averaging out individual convective and storm impulses for which the weather modification potential is not adequately described. Further, present seeding technology is not adequate to respond to these superimposed, generally short lived, cloud and precipitation producing elements.

B. Site Selection

Seven sub-areas of the Colorado River Basin have been considered for a Pilot Project. These sub-areas representing only about 13 percent (about 14,200 square miles) of the Colorado River Basin (about 109,500 square miles), account for the major portion of the streamflow. The average annual runoff from the Basin is equivalent to about 2.3 inches of precipitation (Crow, 1967). The sub-areas selected for consideration produce a runoff equivalent to 10 inches or more of precipitation. Another portion of the Basin, some 9,500 square miles, produces from 1 to 10 inches of precipitation and the remainder of the Basin, some 85,800 square miles, produces runoff equivalent to about one inch of precipitation or less. This large difference in water yield of various portions of the Basin results from (1) substantially greater amounts of precipitation in the mountainous areas resulting from orographic influences and (2) the greatly increased evapotranspiration losses at lower elevations. Clearly, the initial stages of a weather modification adaptation program in the Colorado River Basin should be concentrated in the 13 percent of the Basin that produces over 10 inches of precipitation and about 77 percent of the annual runoff. This portion of the Basin lies almost exclusively above about 9,000 ft. elevation. The 9,000 ft. contour consequently has been used to define sub-areas of the Basin for primary consideration for the initial Pilot Project. Seven areas have been considered and defined in terms of mountain massifs rather than as individual water sheds. While commercial programs of weather modification in mountainous areas have in general been conducted for individual water sheds, moderate or large scale weather modification operations within the Colorado drainage basin will effect a number of such basins. The seven sub-areas that have been considered include: (1) the San Juan mountains; (2) the central massif between the main stem of the Colorado and the Gunnison Rivers; (3) the upper basin of the Colorado River Basin above Kremmling; (4) the White Mountains at the headwaters of the White River; (5) the Park Range and headwaters of the Yampa River; (6) the Uinta Mountains, and; (7) the Wind River Range at the headwaters of the Green River. These areas are shown in Figure 6. After initial analyses areas one and three were selected for primary consideration. The San Juan area (Figure 7) includes drainage areas both north and south of the mountain range and extends to the New Mexico border. The upper basin of the Colorado River area includes drainage areas from Williams Fork to Troublesome Creeks and is shown in Figure 8. The selection criteria for these two areas are discussed in Appendix A: V, C.

A dual effort for these two areas would maximize the benefits from a Pilot Project. The types of storms that produce precipitation for the two areas can be substantially different; the weather modification potential is probably markedly different; and increased flexibility in the experimental design could be incorporated. Costs would of course be substantially increased. The San Juan Mountains,



UPPER COLORADO RIVER DRAINAGE BASIN

Figure 6.

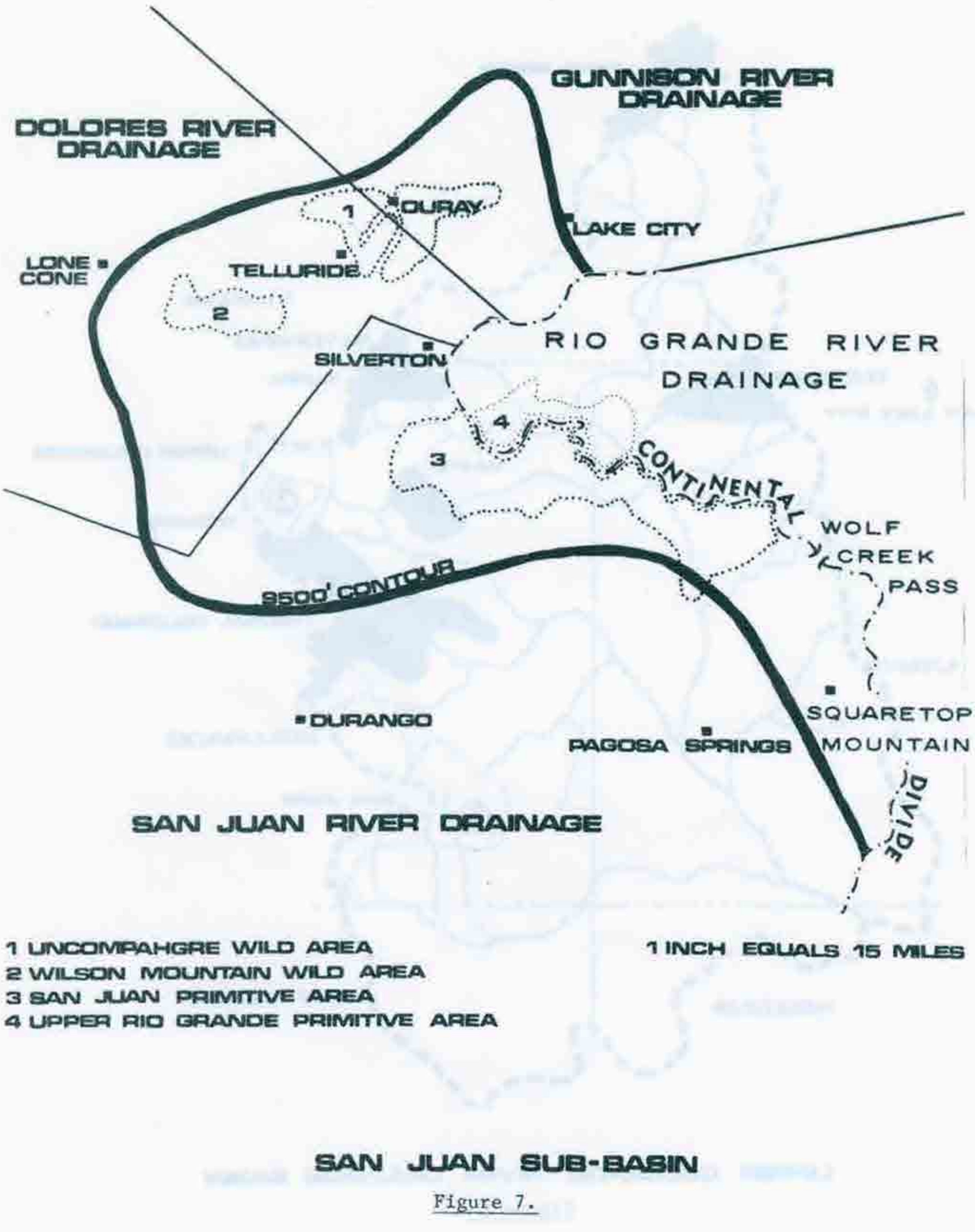

GUNNISON RIVER DRAINAGE
DOLORES RIVER DRAINAGE
1
OURAY
LAKE CITY
LONE CONE
TELLURIDE
2
RIO GRANDE RIVER DRAINAGE
SILVERTON
4
3
CONTINENTAL
WOLF CREEK PASS
9500' CONTOUR
SQUARETOP MOUNTAIN
DURANGO
PAGOSA SPRINGS
DIVIDE
SAN JUAN RIVER DRAINAGE
1 UNCOMPAHGRE WILD AREA
2 WILSON MOUNTAIN WILD AREA
3 SAN JUAN PRIMITIVE AREA
4 UPPER RIO GRANDE PRIMITIVE AREA
1 INCH EQUALS 15 MILES
SAN JUAN SUB-BASIN

Figure 7.

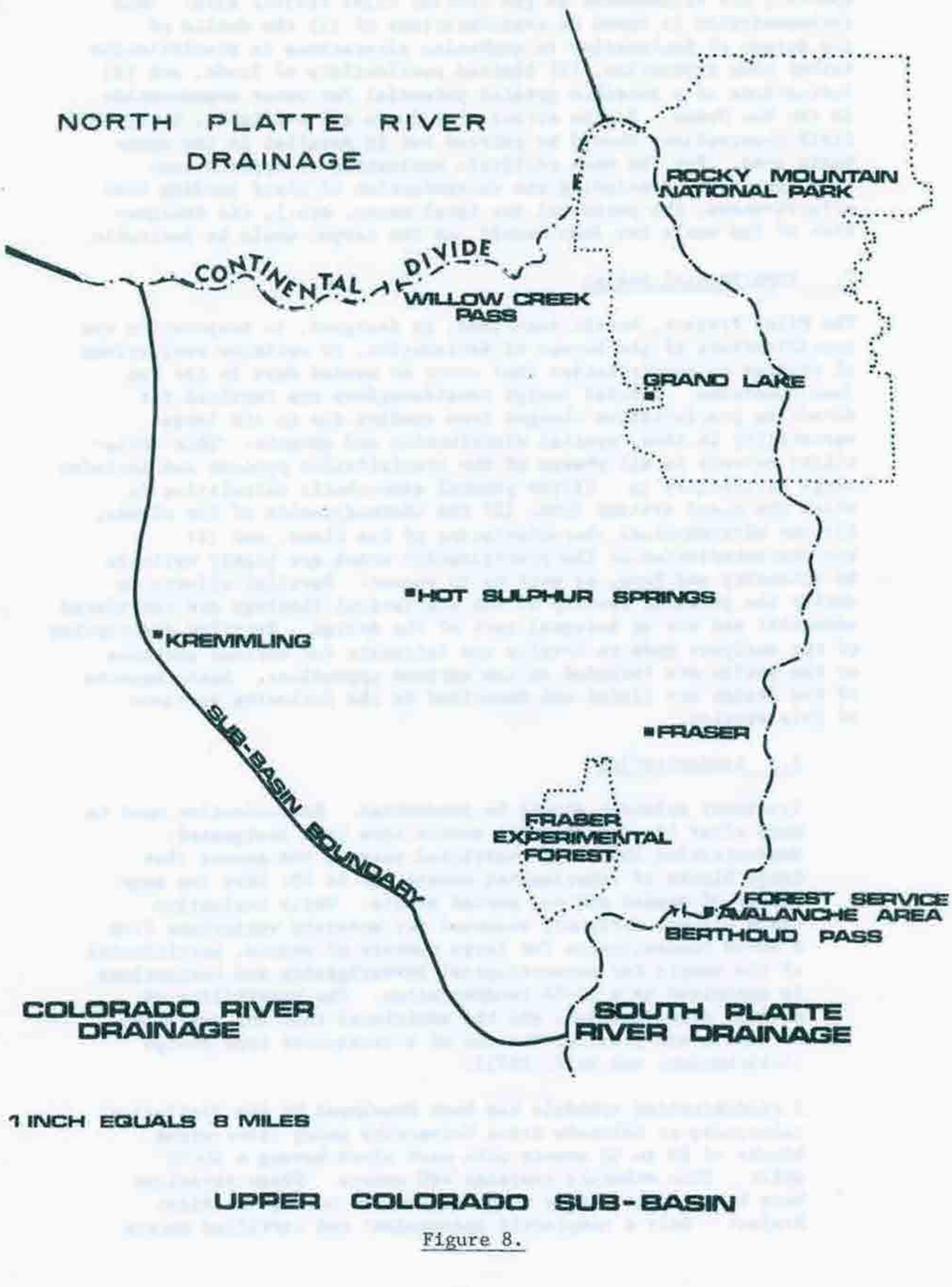

NORTH PLATTE RIVER
DRAINAGE
ROCKY MOUNTAIN
NATIONAL PARK
CONTINENTAL DIVIDE
WILLOW CREEK
PASS
GRAND LAKE
HOT SULPHUR SPRINGS
KREMMLING
SUB-BASIN BOUNDARY
FRASER
FRASER
EXPERIMENTAL
FOREST
FOREST SERVICE
AVALANCHE AREA
BERTHOUD PASS
COLORADO RIVER
DRAINAGE
SOUTH PLATTE
RIVER DRAINAGE
1 INCH EQUALS 8 MILES
UPPER COLORADO SUB-BASIN

Figure 8.

however, are recommended as the initial Pilot Project site. This recommendation is based on considerations of (1) the desire of the Bureau of Reclamation to emphasize alterations in precipitation rather than streamflow, (2) limited availability of funds, and (3) indications of a possible greater potential for water augmentation in the San Juans. To the extent that funds are available, background field observations should be carried out in parallel in the upper basin area. For the most realistic evaluation of application-type operations (including the determination of cloud seeding cost effectiveness, the potential for total water, etc.), the designation of the whole San Juan massif as the target would be desirable.

C. Experimental Design

The Pilot Project, herein described, is designed, in response to the specifications of the Bureau of Reclamation, to optimize evaluations of changes in precipitation that occur on seeded days in the San Juan Mountains. Careful design considerations are required for detecting precipitation changes from seeding due to its large variability in time, spatial distribution and amounts. This variability extends to all phases of the precipitation process and includes large variability in (1) the general atmospheric circulation in which the cloud systems form, (2) the thermodynamics of the clouds, (3) the microphysical characteristics of the cloud, and (4) the characteristics of the precipitation which are highly variable in intensity and form, as well as in amount. Parallel efforts to verify the physical reality of the statistical findings are considered essential and are an integral part of the design. Detailed description of the analyses made to develop the rationale for various portions of the design are included in the various appendices. Basic aspects of the design are listed and described in the following portions of this section.

1. Randomization

Treatment episodes should be randomized. Randomization must be made after the experimental events have been designated. Randomization should be restricted only to the extent that large blocks of experimental events (10 to 40) have the same number of seeded and not seeded events. While evaluation tests are not seriously weakened for moderate variations from a 50-50 randomization for large numbers of events, partitioning of the sample for meteorological investigation and evaluations is maximized by a 50-50 randomization. The possibility of seeding contamination, and the additional cost for operation of dual areas preclude the use of a cross-over type design (Schickendanz and Huff, 1971).

A randomization schedule has been developed by the Statistical Laboratory at Colorado State University using inter-mixed blocks of 10 to 40 events with each block having a 50-50 split. This schedule contains 400 events. These decisions have been consecutively numbered for use during the Pilot Project. Only a completely independent and certified source should have access to the decisions. The handling and release of randomization decisions after experimental days have been officially declared, by a certified official at Ft. Lewis A and M College in Durango, would provide a good procedure. Several other arrangements are feasible. To preclude any possibility of bias, or appearance of bias, it is crucial that no one have knowledge of upcoming randomization decisions. Once the experimental program and the randomization scheme are finalized, it is important that they are not substantially altered during the experiment.

2. Experimental Period

This design is for the seeding of winter time orographic cloud systems. It is not designed as an experiment for seeding cloud systems that are caused by convection or large scale storms. It takes into account, by averaging over a large number of hours of precipitation, meteorological episodes that do have some component of the precipitation caused by convective and large scale cloud systems. (Note Section V, A, above). These design criteria place constraints on the period of the year during which the field program should be operated. Basically the operations period should be from 1 November through 30 April each year. Discretion should be used, particularly during November and April, in not including situations for which convection and general storm conditions are the overriding cause of clouds and precipitation. On the other hand, situations sometimes occur in October and May during which nearly steady state orographic lifting is the dominant cause of clouds and precipitation. These could be considered for operations.

3. Experimental Unit

A twenty-four hour experimental unit is recommended. This length of unit is a compromise that minimizes variations in physical parameters during an event and should still be long enough to reduce contamination among experimental units to a reasonably low proportion of the total unit (amount of time, amount of precipitation). Auto-correlations of daily precipitation in the Colorado River Basin are not sufficiently high to justifypairing consecutive randomization days. From the standpoint of contamination, a procedure for leaving non-experimental days between experimental events would be desirable. This, however, would create a serious loss of events in an experiment planned for only four years. The analysis of ice nuclei observations and precipitation data in the Climax area has shown that while carry-over effects have been observed using the twenty-four hour unit, these have not been of the magnitude to critically disrupt the analysis. Since they represent contaminated effects that may increase precipitation on not seeded days, they may decrease the magnitude of indicated seeding effects. The minimization of contamination carry-over effects was simplified at Climax due to the diurnal variations in precipitation where a very marked minimum in hourly precipitation occurs during the morning hours from about 0700 to 1100 MST. This follows a very marked diurnal maximum precipitation during the night-time hours (Appendix A: V; D and C). A similar diurnal variation in precipitation occurs in the San Juan area during the morning hours, although it is not as distinct as at Climax. The precipitation data at Durango actually shows a mid-morning peak in precipitation. It seems clear, however, that in most of the San Juan Mountain area the relative percent of daily snowfall occurring during the mid-morning hours is near a minimum. A mid-morning starting time for an experimental day should thus be used. It should minimize contamination effects. Further, observations during morning hours will minimize any melting effects where snowboards are used. A twenty-four hour experimental unit starting at 1000 to 1100 MST would have many experimental and operational advantages. There is also a distinct advantage with this transition time since the very comprehensive 1200 GMT data base can be used in making operating decisions.

4. Declaration of Experimental Days

A sequence of analysis procedures should be used for establishing experimental days. The sequence should include: (a) a forecast of meteorological conditions that could produce orographic clouds; (b) a forecast of positive weather modification potential; and, (c) an evaluation of possible hazards and disbenefits that might be related to additional precipitation.

a. Forecast of Orographic Clouds and/or Precipitation

The required meteorological forecast involves a substantial deviation from procedures that would be followed in a true application-type seeding program. This occurs since an experimental day must, for randomization purposes, be declared before it starts rather than just prior to the development of seedable conditions (a forecast of 24-30 hours rather than one of 1 - 3 hours). Effects of this undesirable forecast requirement can be alleviated somewhat, by providing for the declaration of some experimental days after they are actually under way. The experimental day for evaluation purposes must still coincide with the 1100 to 1100 twenty-four hour day. Daily precipitation totals are frequently made up of precipitation episodes that last for only relatively few hours. In many cases these precipitation episodes can be expected to occur during the later part of a twenty-four hour specified period with the first portion having generally clear skies throughout the San Juans. Forecasting the timing on these episodes for a period of twenty-four hours in advance can be rather difficult. Declaration of experimental days in these cases can be delayed for some 12 to 15 hours and still not compromise the experiment. A declaration of an experimental day later than half way through the experimental period, 11 p.m., is not recommended. Procedures must also be available when a delayed declaration is made for obtaining the random decision after the declaration. In cases when the forecast is for no clouds and precipitation, the day can be declared "non-experimental" and steps "b" and "c" of the declaration procedure as described below can be omitted.

Forecasts of orographic clouds must of necessity utilize standard short range weather forecasting techniques. These can and should be refined in forecasting orographic clouds for the specific Pilot Project areas. General guidelines are prescribed in Appendix E and tested forecast criteria have been presented and discussed by E. G. & G. (1970). Forecast emphasis needs to be placed on optimizing the forecasts of: (1) wind direction and velocity at about the 700 mb level; (2) moisture potential (700 mb dew point depression constitutes a good indicator); (3) the nature of the large scale vertical motion field (say, using vorticity indices); and, (4) static stability of the air mass.

b. Forecast of Weather Modification Potential

The determination of the weather modification potential is based on meteorological criteria, and this also introduces forecast complications. Again this problem is considerably greater than it would be in a true application-type program.

As discussed in Sections III, A, and V, A, above, the basic model for the experiment involves seeding for orographic clouds that remain quasi-stationary for many hours. During these situations when very short period meteorological variations occur, operational changes frequently are not feasible. Thus, in application-type seeding operations lasting several to many hours, seeding can,except where a definite trend exists, be carried out continuously for many hours and extend beyond arbitrary daily time boundaries.

The specific criteria for specifying desired conditions are those defined from previous field experiments. One criteria for weather modification potential is that the air flow must be toward the mountain slopes. A second criteria to define potential should be based on cloud temperatures (model considerations show that cloud top temperature that defines ice crystal concentrations is basic). To maximize scientific results, seeding should be carried out for all temperatures and analyses made for various temperature categorizations throughout the temperature range. Since in the Pilot Project emphasis is placed on providing precipitation increases, specification of temperature criteria is required. Modeling and previous experiments show that a criteria of average cloud top temperature of -23°C or -24°C and warmer should provide a data sample that would maximize the potential for increasing precipitation. A cutoff criteria of about -26°C would increase the sample size, simplify the forecast problem, and should not produce precipitation decreases except when actual temperatures are colder than forecast. These criteria require observations of average cloud top temperatures (they may be lower or higher for periods during the seeding period). These might be made with radar, satellites, aircraft, etc: tests at Climax, using radar and aircraft as reference, have shown only some 60-70% success in making good cloud top estimates from upper air soundings. When required cloud top data is not available, 500 mb temperature can be used to index the cloud top temperature since average orographic cloud tops in the Pilot Project area extend to about this level. The 500 millibar level has the advantage of being a standard level reported for upper air soundings. At both Climax and during the previous Colorado State University Wolf Creek experiments the temperature at this level was a good index to seeding potential and is probably very close to the "average" orographic cloud tops. Analyses of previous experiments have also shown that the use of 700 mb equivalent potential temperature could serve as a satisfactory index for defining seeding potential. The use of 700 mb equivalent temperature not only describes cloud temperature, but reflects moisture availability, and is independent of an actual measurement of the cloud top. Greatest precipitation increases in all portions of the target for specific temperatures should be expected at 700 mb equivalent potential temperatures above about 310°K. Substantial increases on the upwind mountain slopes can also occur with 700 mb θ_e values from 295° to 310°K - particularly at the lower elevations of the target area. When 700 θ_e criteria are used, a temperature of about 295°K or greater should indicate an overall potential for augmenting precipitation without a serious threat of causing a decrease. The experience during the CSU Wolf Creek Pass experiment indicates that precipitation displacement effects could cause precipitation decreases in some areas at 700 θ_e values less than 300°K.

Careful records of all days determined to have positive modification potential should be maintained for evaluation purposes. These would constitute days with potential and no restriction to operations.

c. Evaluation of Possible Hazards and Disbenefits

The third stage in the identification of an experimental day involves the determination of the possibilities of disbenefits that might result if a seeding operation is carried out. This becomes important and requires emphasis on those occasions when a cloud situation with weather modification potential has been identified. This is one of the most difficult considerations since many social, economic and ecological interests can be involved. Primary disbenefits can be quantified for consideration.

1. Flooding

Most of the annual peak streamflow on Colorado River tributaries comes during the snow melt season, usually in May or June. In rare years annual peaks may occur in late April on some tributaries or in early July in a heavy snow melt year when weather factors combine to delay the snow melt. Snow melt peaks in streamflow are rarely responsible for substantial flooding in the San Juan area. The annual peaks seldom vary more than about five feet in river stage, and when stream banks overflow, they generally cover only meadow or unoccupied lands near the river. The greatest flood peaks in this area generally occur outside of the snow melt season and result from intense local summer or fall season rainfalls. Most damage from summer time flooding is caused by temporary jams of debris rather than by lack of channel capacity. In September, 1970, two intense storms occurred approximately one week apart, each lasting for two or three days. The entire stream flow amounts measured at Durango and Placerville for the Animas and San Miguel watersheds both showed peak daily amounts for the entire year. The daily peak for September 6 on the Animas River was measured as 7740 cubic feet per second. This compares with the peak day during the snow melt season on May 19, 1970, of only 4240 cfs. At least at this stage of the Pilot Project, no seeding operations should be scheduled during the summer season. The technology for seeding the summer convective clouds is not well developed. Further, precipitation during this season makes only a small contribution to the total annual streamflow. An analysis of four summer seasons, 1966 through 1969, showed a net production in runoff reaching the Animas River from summer precipitation ranging from 9% of the June - September precipitation in 1966 to 21% of the June - September precipitation in 1969.

The probability of more than minor flood damage from snow melt can be evaluated by considering previous relationships between accumulated snow pack and streamflow. Peak streamflow from snow melt is moderately well related to total streamflow for the snow melt season. The typical probability of more than minor flood damage for tributary streams of the San Juan Basin during the snow melt season is shown in Figure 9. The background for this figure and the other considerations of evaluation of snow melt potential and flooding potential are shown in Appendix A, Part V, E. The historical probability of the occurrence of more than minor flooding is about .04 or about 1 year in 25. It can also be noted that as long as the snow pack does not exceed 50% above normal, the likelihood of flooding from snow melt is negligible. Flooding potential remains

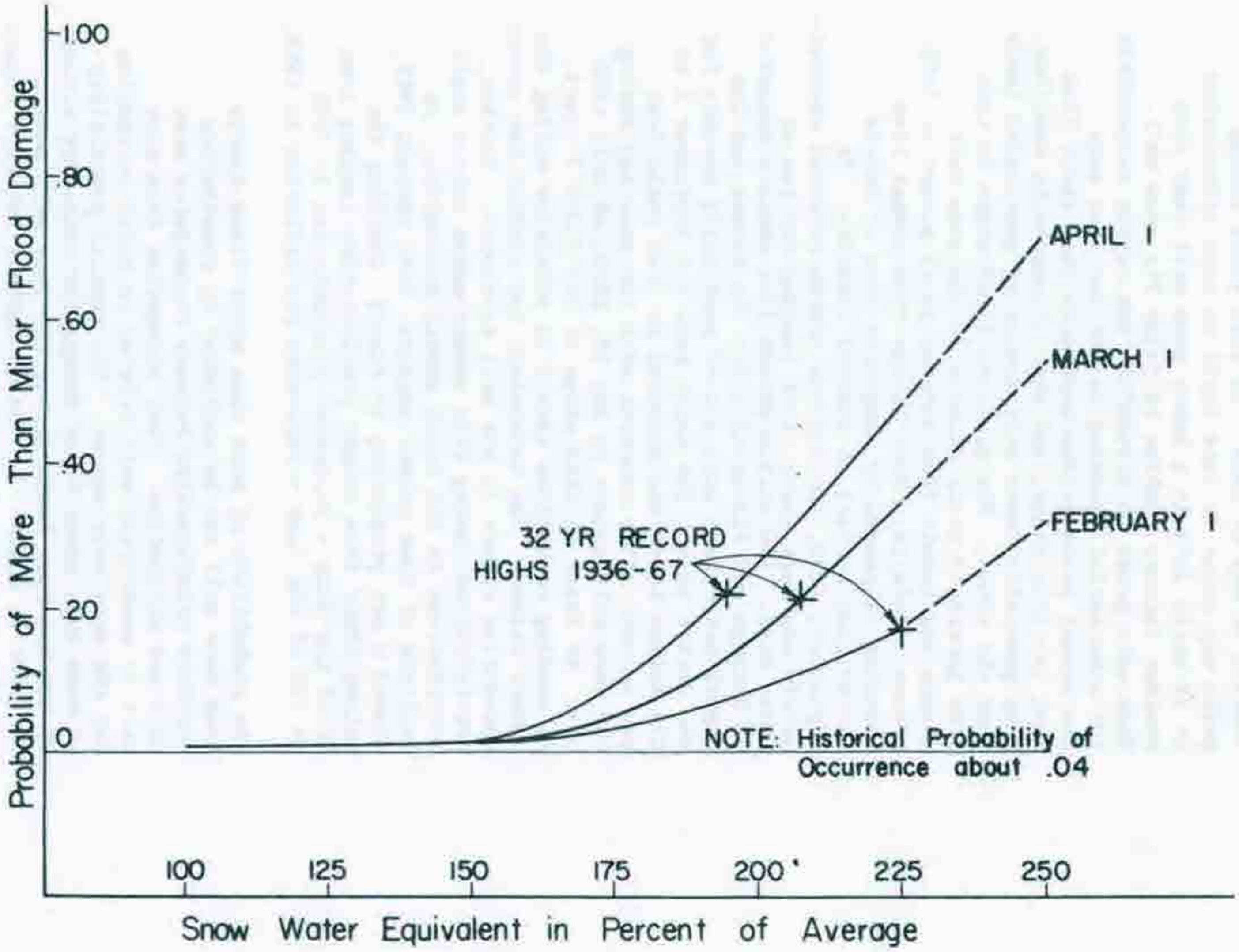


Figure 9. Typical probability of more than minor flood damage for tributary streams to the San Juan during snow melt.

less than about 20% even when the snowpack increases to about 225% of normal on February 1, 210% above normal on March 1 and about 195% normal on April 1. The flood potential probability remains less than about 10% even with February 1 snowpack up to about 200% of normal or March 1 values to about 180% of normal, and April 1 values to about 175% of normal. Figure 9 provides the basis for setting criteria for evaluating the likelihood that seeding increases would contribute to a flood threat in the following spring.

2. Avalanches

The state of the art for evaluating the threat of avalanches, particularly in the San Juan Mountain area, is in a primitive stage of development. The primary threat occurs during the early season in December and January. At the present stage of development the best procedure would be to use a specifically prepared avalanche forecast by the Rocky Mountain Forest and Range Experiment Station. Probability forecasts based on meteorological criteria have been considered by Rhea (E. G. & G., 1970). These probabilities can provide guidelines for defining the risks involved during specific meteorological episodes. From a research, and probably from an economic standpoint, suspension of seeding ooerations during avalanche periods is a serious restriction, since an important portion of the weather modification potential occurs during these events. The possibility of establishing seeding effects is reduced by eliminating this potential from the seedable sample. From the economic standpoint, withholding of operations during these periods involves important losses in potential water supplies. Alternatives to operational suspensions during avalanche periods should, consequently, be considered. These include: (1) avalanche management; (2) traffic control; and, (3) the construction of protective structures and sheds. Preliminary analyses suggest that the value of water production during potential avalanche situations should be great enough to justify the cost of finding an alternative to a direct elimination of operations. A systematic avalanche control program is probably the best economic alternative. Preliminary estimates indicate that this would add only a few cents per acre foot of water produced. As with the other alternatives, a side benefit would be a substantial reduction of the avalanche threat that presently exists even in the absence of weather modification efforts. Most of the slopes which produce avalanches of danger to human activities in the San Juans have probably already been identified. Forecast procedures under development and improved knowledge of the structural stability of cornice snow should permit the artificial removal of snow from critical slide areas before accumulations become excessive and produce an avalanche threat.

3. Economic Considerations

Systematic seeding operations in the San Juan Mountains may cause disruptions in some business, agricultural, and private activities in the area. One of the goals of the Project should be the development of methods for determining the magnitude of disbenefits and ways by which water users could compensate other parties when losses or disruptions do occur. Preliminary analyses (Appendix I) show that the total additional costs for water produced by compensating for disbenefits might be of the order of \$.30 to \$.40 per acre foot. For example, indirect costs of additional snow removal and the loss of personal income due to mine closing, etc., might add from \$.15 to \$.19 per acre foot. Items such as traffic delays caused by additional snow might increase costs by about \$.15 per acre foot. Even when some \$.30 to \$.40 per acre foot of water is added to direct costs, estimated to be in the range from \$0.91 to \$1.15 an acre foot of water produced, the cost of added water is very competitive with costs for obtaining additional water supplies by other means. The establishment of administrative procedures and legal authority for compensation to parties who suffer any disbenefits will require careful study and review by all concerned.

5. Duration of Experiment

The results from the Climax and Wolf Creek Pass experiments can be used to estimate the length of time required to obtain significant results from the Pilot Project. Figures 10 and 11 show the length of time required to obtain statistically significant results in the San Juan area if the results are similar to those obtained, respectively, in the Climax and Wolf Creek Pass experiments. These are the times (shown both for years and events required) that provide a 50% chance of obtaining significance at the 5% level with a one-sided test. It assumes that the frequency of storms during a Pilot Project period is the same as the average frequency during the 1964-70 period and that 1/2 of all seedable events are actually seeded. The additional assumption for the Climax comparison is that the weather modification potential in the San Juan area is the same as at Climax. This is probably a conservative estimate since physical model considerations and the Wolf Creek experiment indicate that the potential in this area is greater. Note from Figure 10 that applying results

FIGURE 10. Time (years or events) required with different 500 mb temperature design criteria to detect changes in precipitation comparable to those found during the Climax randomized experiments. This is the time interval to provide a 50 percent chance of obtaining significance at the 5 percent level with a one-sided test. It assumes that (1) the weather modification potential in the San Juan is the same as at Climax, (2) the frequency of storms in any given year in the San Juan area is the same as the average frequency during the 1964-1970, and (3) 1/2 of all seedable events are actually seeded.

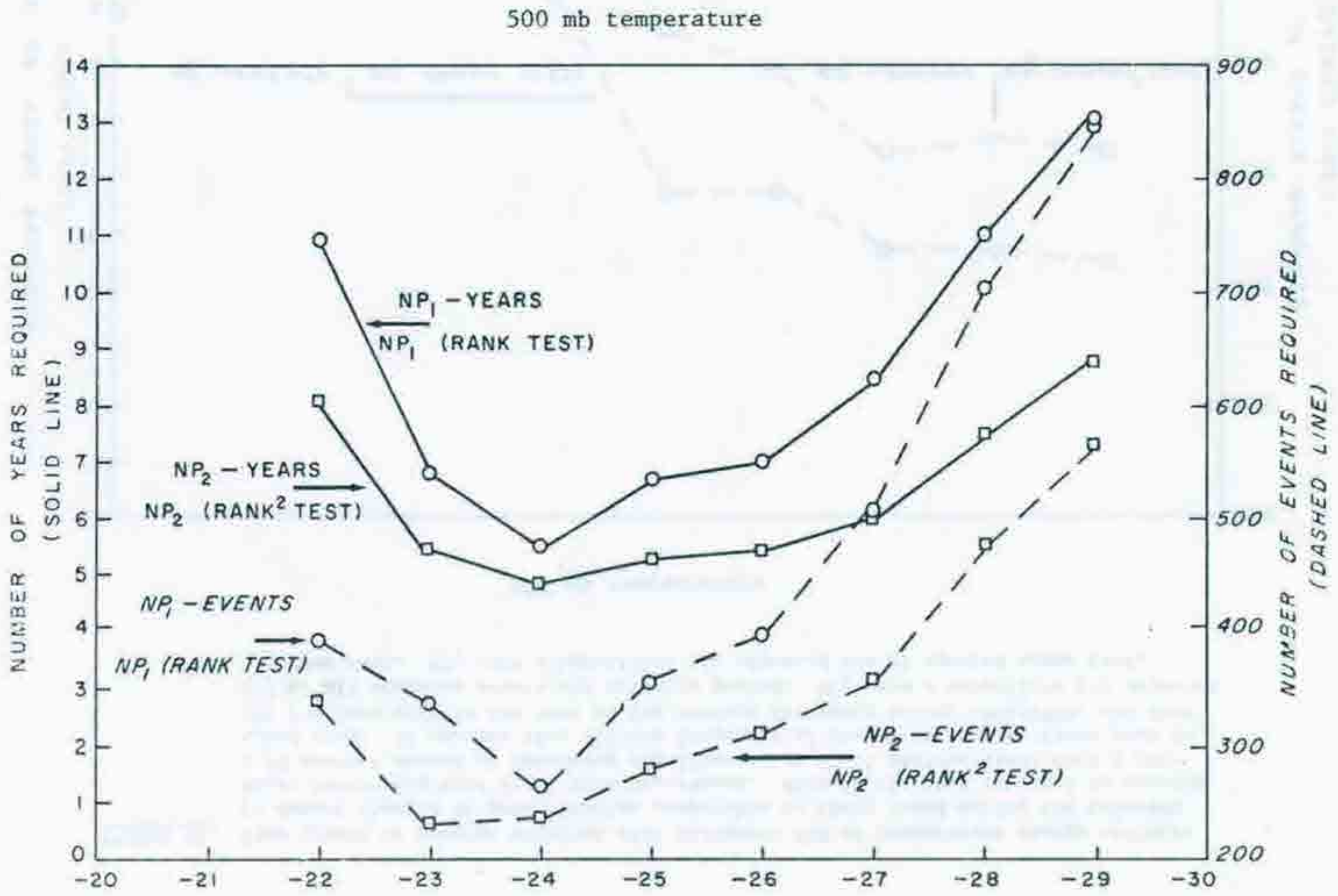
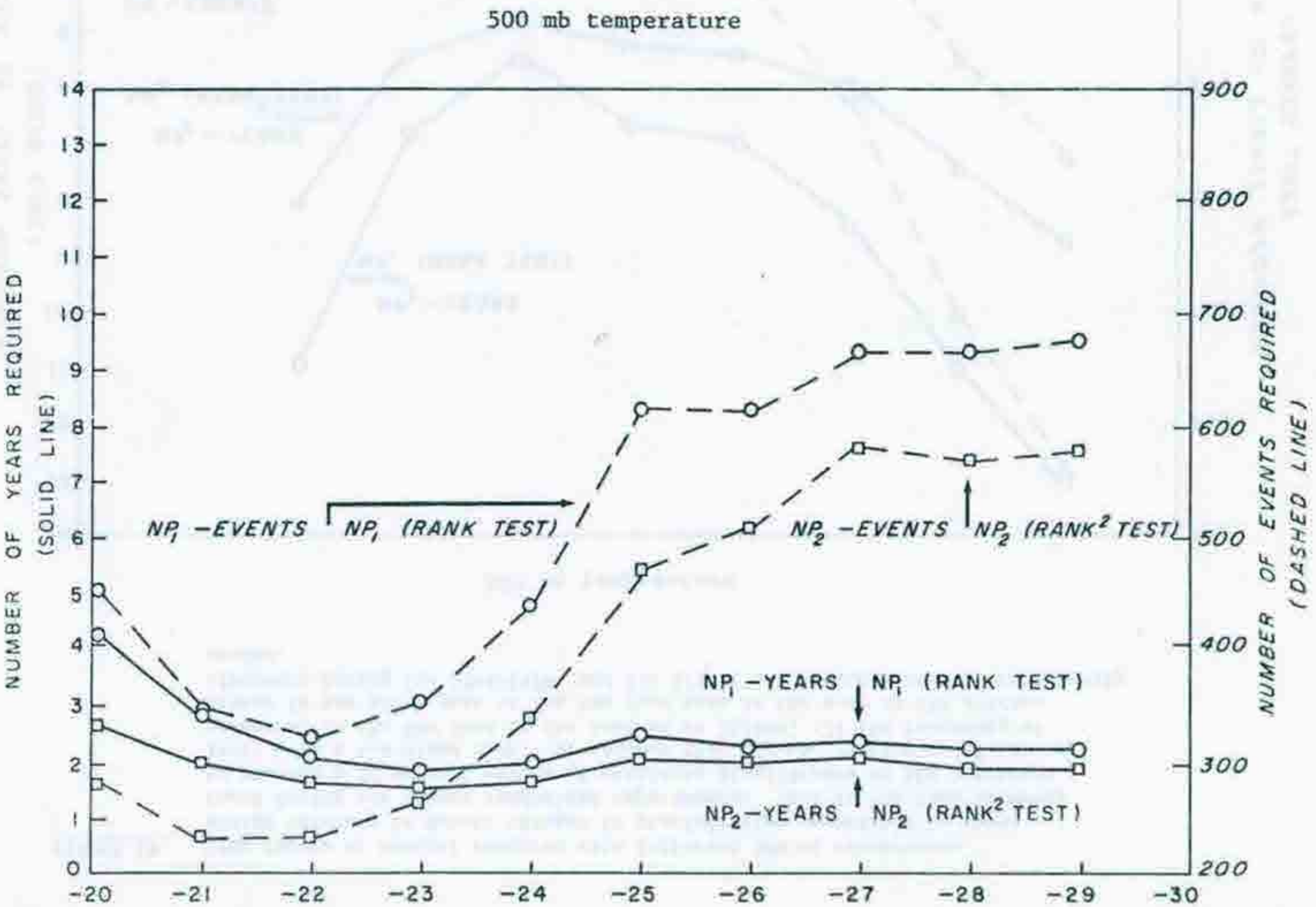


FIGURE 11. Time (years or events) required with different 500 mb temperature design criteria to detect changes in precipitation comparable to those found during the Colorado State University Wolf Creek Pass Experiment. This is the time interval to provide a 50 percent chance of obtaining significance at the 5 percent level with a one-sided test. It assumes that (1) the frequency of storms during any given year in the San Juan area is the same as the average frequency during 1964-1970, and that 1/2 of all seedable events are actually seeded. NP_1 uses a normalized tie adjusted Wilcoxon test. NP_2 uses a normalized tie adjusted sum of squared ranks test.



similar to those obtained at Climax, but using frequencies of 500 mb temperature observed at Wolf Creek, that an experiment lasting five years or more will likely be required. Note also that a cutoff temperature at about -24°C requires the shortest experiment. As seen from Figure 11, a much shorter experiment would be required if Pilot Project results are similar to those observed during the Colorado State University Wolf Creek Pass experiments. The minimum duration occurs with a 500 mb temperature of about -22°C or -23°C, but the experimental duration is not nearly so dependent on specific values of 500 mb temperature. This results from the high frequency of events at warmer temperatures where large precipitation advantages are observed. Some sixty five (65) percent of the events (all days with precipitation at any station) during the Wolf Creek Pass experiments had 500 mb temperatures $\gtrsim$ -23°C. Eighty-four (84) percent had temperatures $\gtrsim$ -26°C. Significance remains high even though the total precipitation differences are reduced at the colder temperature. It must be emphasized that these experimental periods are based on the assumption that 1/2 of all seedable events are actually seeded. The time requirement increases in direct proportion to the number of seedability events not seeded for whatever reason -- seeding restrictions, missed forecasts, inoperative equipment, etc.

D. Data Collection

The extensive collection of field data is required for the Pilot Project. Two types of data are needed: (1) data necessary for statistical and physical evaluations; and, (2) data required for conducting an efficient seeding operation. Portions of these data can have a dual use and serve both of these requirements.

1. Data Requirements for Evaluation

Various types of interpretation must be emphasized in the evaluation. The primary objective of the Pilot Project, however, is to determine the difference in 24-hour precipitation amounts between seeded and not seeded events. This requires emphasis on the collection of daily amounts of precipitation that coincide with the experimental units. Evaluation at other levels of control are specified as a verification of the reality of observed precipitation changes and as a base for assessing the operational efficiency of the program. These supplemental evaluations require information ranging from ice nuclei concentrations and activation characteristics to quantity and timing of streamflow.

a. Precipitation

A relatively even distribution of recording precipitation gauges should be placed throughout the sub-basins of the Pilot Project area. Analyses by Crow (1969) and by

Mielke et al (1973) show that a dense network of gauges is not required to characterize winter time precipitation over a specific portion of the mountain range. A good distribution of gauges along the range, however, is crucial since orographic precipitation effects are highly sensitive to wind direction and velocity. Considerable variation in the portion of the target area which is normal to the airflow can occur since the orientation of the range varies from nearly west to east with a systematic change to nearly north to south. In at least one portion of the range a transect with gauges every few miles should be maintained (over Wolf Creek due to its accessibility) so that possible alteration in elevation changes in snowfall can be evaluated (Mielke et al, 1970). Precipitation gauges and/or snowboards along the highway should be read daily, although recording gauges would be as economical over a period of even four years. Other gauges in the target area should be hourly recording types since these would reduce site visits and maximize the value of the data for evaluation purposes. All gauges should use wind shields and should be mounted on pedestals so that the height of the gauges above the increasing snow surface can be maintained nearly constant. The following are general recommendations for the positioning of the gauges. These are listed by sub-basins. The gauges in the respective sub-basins should be located above 9,000 ft. elevation if possible and preferably in the elevation range from 10,000 to 11,000 ft. In the event that sites above 9,000 ft. are completely impractical, they should be at the highest elevation possible. In selecting the specific location for the respective sites the uniform tree line to the windward of the gauge at an angle of approximately 30° is desirable. Angles of uniform vegetative shielding to as low as 15° to 20° can give good results. Vegetative cover to over 45° from the site and intermittent cover, such as is provided by a few isolated trees, are undesirable. The following are minimum densities recommended for the variable sub-basins for the portion of the San Juan Mountains east of Durango to the New Mexico border.

1. Blanco River	2 gauges
2. Upper San Juan River (Supplement of additional gauges over Wolf Creek Pass.)	9 gauges
3. Upper Piedra River	4 gauges
4. Upper Los Pinos River	3 gauges
5. Vallecito	2 gauges

The above should give a reasonable description of precipitation in the Pilot Project. The minimum of two gauges in each sub-basin is very important since it gives a duplication of readings that can be most helpful in cases of missing data. Gauge concentrations in any of the sub-basins could be increased to advantage from the standpoint of evaluation. Various analyses as referenced above, however, show that this may not justify the additional cost. As is discussed in the section under Operations the telemetry of the data from several of these sites can provide extremely valuable information for operational control and still have full value for evaluation.

Additional precipitation gauges should be installed in upwind and/or unseeded mountain areas to serve as a control for target-control evaluations and for considering extra area effects. A reasonable distribution and concentration of these gauges in various river basins would be:

1. Los Animas River ≈ 4
2. Delores River ≈ 4
3. The San Miguel River ≈ 2
4. The Uncompahgre ≈ 2
5. Lake Fork ≈ 2

Additional gauges are recommended for other sub-basins that are primarily downwind of the target area and will be invaluable for considering downwind or extra-area effects. The sub-basins and the gauges recommended include:

1. Upper Rio Grande River ≈ 4
2. South Fork ≈ 2
3. Alamosa Creek ≈ 2
4. Conejos Creek ≈ 2
5. The Sangre de Cristo Range ≈ 4
6. The eastern slopes of the Sangre de Cristo Range ≈ 2

A distribution of precipitation and gauges as described above would involve approximately fifty units made up of approximately 20 in the target area, 14 in the primarily upwind areas, and 16 primarily in the downwind areas. These are supplemented by the data from the National Weather Service gauges already available. Any data available in the area from existing snow courses, storage precipitation gauges, or snow pillows providing only snowfall totals should be systematically collected and considered but will not be of primary value in analyses of the comparison of seed versus not seeded day precipitation. Consequently, no supplemental expenditures for the collection of this type of data are recommended.

From the standpoint of the target area, the ≈ 20 well distributed gauges over the target area of approximately 930 sq. mile (area above 9,000 ft. mean sea level) would constitute an average gauge density of 1 per 62 sq. miles. The average gauge density for the Wolf Creek area would be approximately one per 46 sq. mile

b. Streamflow

Some attention should be directed to the collection of additional streamflow data but it should not be emphasized. Streamflow analyses should provide a useful supplement to the analysis, even though this analysis is weakened by seeding only a portion of events that contribute to the annual runoff. An average of a 19 percent increase in streamflow was indicated using annual randomization in the Wolf Creek Pass experiment conducted by Colorado State University during the period 1963-64 through 1969-70. The probability of streamflow for the seeded years equaling or exceeding this value by chance alone is less than 1 percent. This program involved seeding of all opportunities. The results were achieved in a six year experiment during which 3 randomly selected years were seeded (comparisons were with not seeded and historical years). In a Pilot Project for which daily randomization is used, only half of the events would be seeded as a maximum. Restrictions to seeding and forecasting problems can be expected to further reduce the proportion of actual seeding events. It is reasonable to expect that actual seeding will take place during only one-fourth to one-third of the hours when seeding potential exists. If these estimates are applied to the indicated streamflow increase of around 19 percent, found during the Colorado State University Wolf Creek experiment, the annual streamflow increase would be of the order of five to six percent. The seeding for the Wolf Creek Pass Experiment was not carried out during the entire winter snow accumulation period so the actual increase for full winter time periods even with restriction for randomization and operational restrictions could be several percent higher than the expected 6% to 7%. The period of time required to detect changes of this magnitude, using even the most sensitive tests, would be considerably longer than the planned Pilot Project if water sheds from mountain massifs in other portions of the Colorado River Basin are used for controls in target-control analyses. If nearby streams with correlations comparable to those used in the Wolf Creek experiment are available, changes of this magnitude could be substantiated with acceptable levels of confidence even during a four to five year Pilot Project. Either of these analyses would require established streamflow gauges both in the target and control areas that have a historical data base. No meaningful analysis of annual streamflow changes could be expected from gauges installed only during a period of the planned four year Pilot Project. Consequently data from new gauges could not be advantageously utilized. The primary advantage of additional stations would be to provide a better definition of the streamflow from various sub-portions of the basin (particularly by elevation) and to initiate a data base for use in subsequent research or applied weather modification programs.

c. Radar

The collection and use of radar data is discussed in the section on "Operations" and in the section on "Evaluation".

d. Upper Air

The collection and use of upper air data is also discussed in the sections on "Operations" and "Evaluation". It would be very desirable for evaluation purposes for radiosonde information to be obtained downwind of the Pilot Project as well as in the upwind area as required for operations. This would make possible consideration of air mass changes that arise from crossing the San Juan Mountains and an atmospheric water balance.

e. Other

It is essential that the statistical analyses of precipitation and streamflow data be supplemented by physical data that provide evaluation results consistent with the statistical conclusions. Firm evidence should be obtained to show that (1) the seeding generators do in fact produce the required concentrations of effective nuclei, (2) the seeding materials do move into the target area and target clouds and (3) expected cloud changes do occur.

Equipment to observe ice nuclei concentrations should be operated upwind of and in the target area. Continuously recording equipment would be desirable but is not recommended for routine use since reliable equipment which provides consistently useful data is not available. It is recommended that a Schaefer mixing-type chamber or a rapid expansion ice nuclei counter be employed as the basic observation unit. The rapid expansion chamber has the primary advantage of providing the capability for obtaining nucleation activation spectra from around -12 to near -30°C with relative ease. It can also provide consistent, objectively obtained data even when an operator with minimal training is used. For analysis and evaluation purposes,four and preferably five units should be used for the San Juan Pilot Project. Two of these should be located upwind of the target area at well exposed sites. A site on Mesa Verde is strongly recommended if suitable arrangements can be made. Another should be located further east and between the Jemez Mountain experiment and seeding sites in the San Juan Mountains. The other units should be located in the target area. One of these should be located on the west side of Wolf Creek Pass, preferably in the general area between Four Mile and Turkey

Creek. A fourth site near the summit or just west of the summit is recommended. A location near the present "Wolf Creek West" precipitation station would be an acceptable alternate. A fifth unit at an intermediate elevation, say 7,000 - 9,000 ft. mean sea level and located near the central or western portion of the target area would be highly desirable if resources permit. The first four units are considered essential. Additional data on ice nuclei concentrations entering the cloud systems should be obtained during the early stages of the program, and periodically thereafter, for use in the physical evaluations. Since this is also direct input for the operations program, the collection of this data is discussed later.

Mountainside collection of ice crystals is recommended for the analysis of cloud and precipitation differences between seeded and not seeded events. This data can provide information on crystal shapes, concentrations, and sizes, and on the characteristics of riming as produced by subcooled cloud water. The use of continuous replicators (Hindman and Rinker, 1966) or improved devices are recommended for use at the same sites recommended for ice nuclei counters in the target area and at one additional site to the lee of Wolf Creek Pass. As with ice nuclei, information on ice crystals and cloud droplets from within the clouds should be obtained on at least some representative days under both seeded and not seeded conditions. This is discussed further in the section on "Operations".

2. Data Requirements for Conducting Operations

Data to assist in the control of the seeding operations should include: (a) surface and upper air synoptic data as available on the National Weather Service circuits; (b) radiosonde data from upwind of the target area; (c) surface weather data from within and immediately upwind of the target area; (d) radar data and, (e) ice nuclei data upwind of and in the target area.

a. National Weather Service Synoptic Weather Data

Complete synoptic weather data for the western U. S. should be available in the project field office.

b. Upwind Radiosonde Observations

Supplemental radiosonde observations should be made upwind of the target area. Careful consideration should be given to the possibility that induced characteristics of air parcel lifting in the lower portions of the sounding may already have occurred if a location such as Durango is used. Care should also be taken to ascertain whether systematic temperature and humidity alterations may result at such a location since it is immediately downwind of the mountain range immediately to the west. From an operational standpoint, routine soundings should be made daily at a time several hours prior to the start of each potential experimental day, at the mid-point of experimental days, and as required when substantial air mass changes have occurred or are expected. At least one sounding should be made on all days, including those on which operations are not anticipated. This can provide important background for evaluations. Since the operational concept uses an "average" model, information for continuous changes in operations (not possible in any case) is not required. Information of substantial air mass changes in progress should be reflected in data telemetered from nearby mountain weather stations and available on a continuous basis.

c. Surface Weather Data

The availability of three well-exposed mountain stations from which basic meteorological information can be obtained on call would be extremely valuable to the operations. One station at the extreme western end of the San Juan Mountains would give good advance information on the movement of incoming transitory weather systems. A station in the central part of the San Juan Mountains (say north of Durango) and one toward the eastern portion would provide continuous information of weather conditions in the target. Data from these mountain top sites at 10,000 - 13,000 ft. elevation, when combined with surface observations from the operational base area at 6,000 to 7,000 ft. msl, would provide almost continuous information on changes in the important lower levels of the lifted air mass. Basic elements observed should include wind, temperature, and humidity. If resources permit, elements more complex to observe (cloudiness, precipitation, etc.) should be added.

Selected precipitation gauges (6-10) from the network for evaluation should be equipped to provide telemetered precipitation data on demand as background information for the operations program.

d. Radar

Radar can provide important information of several types. Two of the most important include: (1) information on cloud and/or snowfall tops; and, (2) information on the presence and distribution of snowfall over the target area. The simultaneous collection of these two types of information with one radar over the proposed target can be difficult. It is recommended that emphasis be placed on radar for providing information on the vertical structure of the orographic clouds if the budget for radar is limited. For observing cloud and/or precipitation tops associated with snow (ice) falling at the light precipitation intensities prevalent in the San Juan Mountains, a vertical pointing or vertical rotating radar in the K or at least the X band is required. K band radar can provide the required information on both clouds and light snow particles. X band radar can provide information on precipitation tops for snow crystals to sizes down to about 100 micron radius when present in concentrations at least as low as those required for efficient comsumption of cloud water, around ten per liter. It can thus provide information during most snowfall episodes. It cannot provide information when only cloud water exists or when only a few small ice crystals are present and the precipitation process is naturally inefficient. At least until the technology is developed and nearly continuous information on cloud tops becomes available from satellite observations, radar at the present offers the only practical method of continuously monitoring cloud and/or precipitation tops and should be a basic element of the Pilot Project data collection system. K band radar should be employed if possible. The data can be obtained, hopefully, in digital form, from scope photography, or at least by scope observations. Such data can be an extremely useful tool in making operational decisions and for subsequent evaluations. Attenuation during most conditions would not constitute a serious limitation when the emphasis is on the vertical distribution of clouds and precipitation, since cloud tops at the extreme are at a distance of only four to five miles (generally only two miles) and precipitation is in frozen rather than liquid form. The radar should be located directly under or at least very near to the orographic cloud over the actual target area since range limitations are severe with snowfall at low intensities.

e. Ice Nuclei Data

Ice nuclei data should be collected and routinely available in making operational decisions, since the basic hypothesis on which the project is based relates to available concentrations of ice nuclei. While it is impractical to routinely observe concentrations of ice nuclei entering orographic clouds, helpful data can be obtained with a reasonable effort. Information on ice nuclei concentrations and activation characteristics can aid in evaluating seeding requirements and in following seeding effects. First, concentrations of ice nuclei in the incoming air mass should be monitored. The observations should be made at a point upstream of all seeding generators at a well exposed location. The Mesa Verde site, recommended in the evaluation section for data collection, would be excellent. If cases are found when high concentrations of ice nuclei are entering the area from whatever source, upwind cloud seeding, inadvertent man-made sources, or natural sources, conditions should be considered as not suitable for Pilot Project experiments. Secondly, ice nuclei observations are vital in following the drift pattern of the seeding materials. Patterns of nuclei transport should be established for different combinations of generator operations and airflow. Systematic tracking of materials with instrumented aircraft should be used in conjunction with ground stations at least prior to and in the early phases of program and periodically as the program progresses. Knowledge of the transport patterns of the seeding materials under differing conditions must be established and monitored within the framework of a continuously increasing experience for differing weather conditions.

E. Operations

1. Operations Base

An operations base should be established in the vicinity of the Pilot Project. This facility should be manned and equipped to provide round-the-clock weather surveillance and forecast support for the Pilot Project. Forecast problems relevant to the Pilot Project are expected to include (1) the identification of an "experimental day", (2) short term forecasts of upper winds, temperatures, and moisture distributions pertinent to the real time control of the operations, and (3) longer range weather outlooks needed for planning field activities such as the distribution of supplies, equipment, etc. Facilities and procedures (E.G. & G., 1970) for the accomplishment of these objectives should be available at or controlled from the base. The basic source of meteorological data at this base should be that provided by the National Weather Service data collection and analysis system. This should include teletype circuits, weather teletype circuits and facsimile charts produced at the National Meteorological Center. The operations base should include a well-equipped and manned communications center for contact with the Bureau of Reclamation and with data producing facilities which would be primarily controlled from the operation base. The data producing facilities should include (1) radiosonde and pibal stations, (2) mountain top telemetered weather stations, (3) radar facilities, and (4) ice nuclei sites.

2. Seeding Method

Analyses of randomized seeding at Climax and Wolf Creek Pass strongly indicate that under proper meteorological conditions substantial increases in precipitation can be obtained using ground generators. Even greater increases might be obtained under certain circumstances with direct delivery of seeding material to the desired location within the cloud system. The effect of direct delivery (aircraft) of seeding materials, however, has not been adequately explored and tested under conditions that exist in the Colorado River Basin. The operational efficiency of aircraft can be adversely affected by bad weather. In addition, seeding by aircraft, rockets, or balloons can introduce a serious problem of dilution of the seeding material from the originating point or line source to the desired values within the cloud system. Since ground delivery has been tested in experimental programs with encouraging results, the initial Pilot Project is designed to utilize only this system. The combination of both ground and direct delivery systems would considerably complicate the evaluation and interpretation of results. Seeding by direct delivery should receive consideration in a subsequent Pilot Program.

3. Seeding Equipment and Materials

a. Seeding Generator

The primary consideration in the selection of seeding generators should be that they will deliver at least the concentrations of nuclei prescribed by the physical models for various meteorological situations. The Colorado State University modified Skyfire-type generator has been both laboratory and field tested in the Climax and Wolf Creek experiments and shown to provide large numbers of effective nuclei that are active at temperatures accompanying winter time snowfall in the Colorado River Basin. Other type generators with efficiency at least as good as these units are probably more adaptable to remote telemetry. Skyfire-type generators, however, can serve as a minimum standard for seeding equipment to be used. This type generator has been found to be suitable for manual operations. For both manual and remote control generators, operational reliability as well as nuclei output should be prime prerequisites. The output of the generators should be at least 10^{15} nuclei per gram effective at -20°C and at least 10^{14} per gram effective at -12°C.

b. Seeding Material

A seeding solution of AgI-NaI has been used in previous experiments in the Colorado River Basin. New evidence indicates that a complex AgI-NH_4I instead of AgI-NaI probably produces a higher output of effective nuclei at temperatures warmer than, say about -8° to -10°C. Clouds with top temperatures this warm are very rare in the Colorado River Basin during winter. It is recommended that the AgI-NaI complex be used in the Pilot Project since more field experience with this complex is available, and nuclei tracing and results of randomized seeding have shown that this material does enter and produce large concentrations of ice crystals in Rocky Mountain orographic clouds. Moreover, increases in precipitation are indicated in experiments in which it has been used.

c. Seeding Rate

A variable seeding rate with a capability of from 2 grams per hour per generator to approximately 200 grams per hour per generator is recommended. The use of a variable seeding rate can provide for comparable concentrations of ice nuclei active in the cloud even though the generator nucleation efficiency decreases at warmer temperatures. The following seeding rates are recommended for the respective categories of cloud top (or 500 mb) temperatures.

Temperature	Seeding Rate
equal to or greater $\geq$ -15°C	200 grams per hour per generator
-16 - -21°C	20 grams per hour per generator
-22 - -26°C	2 grams per hour per generator
less than -26°C	no seeding

Strict adherence to model consideration would require more refined variations. This is not recommended since it would greatly complicate generators needed for seeding and would represent an effort well beyond the state of knowledge concerning the dispersion and transport of the seeding materials. From strict model considerations the seeding rate recommended for temperatures equal to or greater than -15°C should be higher than specified. However, indications at both Climax and Wolf Creek Pass in previous experiments are that actual crystal concentrations in this temperature range are higher by a factor of 10 or more than would be expected from considerations of available concentrations of primary ice nuclei. The recommendation of 200 grams per hour per generator in this temperature range is, therefore, an attempt to take these observations into account.

d. Testing of Seeding Generators

Seeding generators should be calibrated in the laboratory and carefully tested under a variety of conditions for operational efficiency in the field. The testing of the generator output under field conditions should be combined with ground and aircraft testing of the transport and dispersion of the seeding material.

e. Generator Sites

The transport and diffusion characteristics of seeding materials in the atmosphere are the least clearly defined aspect of the modification concepts for seeding orographic clouds. No model is available for describing the transport and dispersion characteristics of aerosols over complex terrain. Such a model is under development at Colorado State University using both field and laboratory modeling data but even preliminary versions are not expected before at least the latter stages of the Pilot Project. For some limited conditions the Gifford-Pasquel Model has been used for describing dispersion patterns for seeding materials. This model was not developed for use in complex terrain and has limited application when used in this manner. The recommendations for generator sites in the Pilot Project are based primarily on (1) the field tracing and laboratory modeling of the trajectories of seeding materials in the Climax area, (2) the Colorado State University laboratory modeling of particulate transport in the San Juan area, and (3) the limited field tracing by E. G. & G in the San Juan area (E.G.&G, 1970). The results of the laboratory modeling and field testing for delivery of seeding materials are reported separately (Grant et al, 1968; Cermak et al, 1969; Orgill et al, 1970; Cermak et al, 1969; Orgill et al, 1970; Orgill et al, 1972). The indicated increases in precipitation for seed days during previous experiments clearly indicate reasonably adequate transport of seeding materials into the cloud systems. Further, the good general agreement between actual precipitation and computed available condensate for the Climax experiments in the warm cloud temperature regions indicates a reasonable delivery efficiency.

The basic premise for defining generator sites for the Pilot Project is that the seeding should be conducted to fill the broad canyons leading into the San Juan Mountains. Both laboratory and field observations have shown that valley filling takes place, and that ground generators operated over several hours makes the valley itself the source region. The seeding materials can then be distributed to cloud systems over a period of time by orographic effects, turbulent mixing, and convection. The valley filling can reach a quasi-steady state after several hours and frequently continue for an extended period of time.

It is beyond the scope of the design study to identify specific generator sites. The following are recommended guidelines for specific site selection: (1) Seeding should be conducted to obtain valley filling within the broad canyons so that nuclei concentrations in the range from 10 to 50 per liter will be available in the cloud systems. Precise location of the generators in the broad canyons is not considered critical but careful attention should be placed on avoiding locations conducive to the trapping of cold air pools. (2) Approximately four generators should be used for each broad canyon. This should provide approximately two basic units twenty to twenty-five miles upwind from the main mountain ridge, one or two units at around 10 miles from the ridge for cases of low wind speeds and when materials might be used prematurely, and one seeding unit 40 to 50 miles or more from the ridge for cases with strong winds and when intervening utilization as ice nuclei or destruction of the materials by ultra-violet deactivation is not a problem. Some 16 sites recommended for reconnaissance are listed in 1B of Appendix A. Total generator requirements should be approximately 30, (portion of San Juan Mountains east of Durango-Silverton Highway).

f. Initiation and Termination of Seeding

Since the mean 700 mb wind speed during storms is around 20 mph (Note Figure 42, Appendix A for distribution), generators located in the main generator line at 20-25 miles upwind of the main ridge should be turned on about one hour before the start of a "seed" day and turned off about one hour before it ends. These time increments generally should not be changed substantially for more distant or closer sites since the greater or lesser wind speeds during periods for which they are used constitute an adjustment for the travel time to the target. Generators some 40 miles upwind may need to be started and stopped longer in advance of the "seed" day boundaries and those at around 10 miles may not need as much lead time. This lead time should be adjusted according to wind speeds and expected travel time to the target.

4. Operational Procedures

a. Physical Basis

The physical basis for the Pilot Project has been discussed in III, A and V, A above and in detail in Appendices A and B. The weather modification potential is dependent on the occurrence for extended periods of time of specific airflow and cloud temperatures. The realization of this potential requires artificial seeding for the "average" conditions of the orographic cloud over extended periods. It does not involve a time dependent concept requiring a response to individual perturbations from the average condition: a capability that does not exist. It does involve seeding the orographic component of potential precipitation that may be intermittent during storm episodes as (1) the orographic cloud develops in advance of an approaching storm system, (2) the orographic cloud is intermittently disrupted or has storm or convective components superimposed on it or,(3) the orographic cloud continues after the storm passage. The "average" model places emphasis on the orographic component as having sufficient modification potential to constitute a major part of the total precipitation. The "average" condition may extend for an entire storm episode, but frequently will exist for extended periods associated with differing parts of the storm system. The operational seeding and procedures should respond to this concept of an orographic weather modification potential.

b. Operating Criteria

The following are the recommended basic meteorological criteria delineating weather modification potential for the San Juan Pilot Project: (1) moist air flow toward the San Juan Mountains that is sufficient to produce orographic cloud systems: (2) orographic clouds with cloud top temperatures $\lesssim -26^\circ$C (for operating purposes and $> -23^\circ$C or -24°C for evaluations of physical concepts).

c. Procedure

Operations for the Pilot Project require: (1) the determination of experimental days; (2) declaration of seeded and not seeded days from the randomized schedule; (3) the carrying out of efficient seeding operations on experimental days; and, (4) dedicated measurements of precipitation and other meteorological data required for statistical and physical evaluations.

All aspects of the operation should be carefully documented since the analysis involves both operational and scientific considerations.

1. Determination of Experimental Days

The basic requirement for the declaration of experimental days has been discussed above in Section V, C, 3. From the operational and decision making standpoint this involves:

a. Data collection.
b. Forecasting of the likelihood, characteristics, and duration of orographic clouds.

c. Determination of modification potential for events when orographic clouds are forecast.

d. Evaluation of the necessity for restricting operations due to the possibility of hazards or disbenefits.

e. Declaration of each calendar day as "experimental" or "not experimental". "Experimental" simply means that the day is forecast to have potential for increased precipitation from modification and that no substantial hazards or disbenefits would result from the operation.

2. Declaration of Seeded and Not Seeded Days from Randomization Schedule

The declaration of seeded and not seeded days from the randomization schedule must be made <u>after</u> the declaration of an experimental day. The forecaster must have <u>no knowledge</u> of the seeding decision to follow when he makes a declaration of an experimental day. Randomization procedures are described above in Section V, C, 1.

3. Carrying Out Efficient Seeding Operations

The conduct of efficient seeding operations requires:

a. A proper decision of the requirement for seeding. This involves not only the proper declaration of a seeding day but the proper decision as to seedability as the operations are carried out.

b. Properly directed operations. This involves the proper determination of the airflow and of the generators required. Estimates of transport times must be based primarily on wind speeds, atmospheric thermal stability and specific terrain controls. Plume widths, heights, nuclei concentrations, and distance relationships for seeding materials released in mountain areas are shown in separate reports (Orgill et al, 1969; Cermak et al, 1969) and specifically for the San Juan area (Orgill et al, 1972; E.G. & G., 1970). These relationships are based on laboratory modeling and field measurements.
These relationships are based on laboratory modeling and field measurements. These should be supplemented with field observations and determinations specifically for the Pilot Project area.

c. Efficient communication of operational directions to the generator sites. The directions to the generator operators or to the remotely controlled units must be timely and accurate. Procedures need to be established to routinely verify the implementation of the operational instructions.

d. Efficient operation of the seeding equipment.

e. Control and alteration of the operation as required. This involves appropriate turn on, turn off, and turn on of new generators as wind changes occur.

f. Efficient termination of operations when the seeding or experimental episode ends and/or the meteorological or modification potential becomes unfavorable.

4. Observations of Meteorological Data, Precipitation, and Cloud and Atmospheric Variables

A vital part of the operations program is the systematic data collection to meet the requirements of the evaluation. These data requirements have been described in Section V: D, 1 above. The same care and effort must be exerted in making the observations on all experimental days, whether they are seeded or not seeded.The observers of basic portions of the precipitation, cloud physics, and streamflow data should not be aware of the declaration of seeded or not seeded events. Objectivity should be maintained through the using of recording systems whenever possible. This is particularly true for data which is also used for conducting the seeding operations, i.e., radiosonde, radar, some precipitation data (not most),etc.

F. Evaluation

The San Juan Pilot Program involves (1) efforts to verify and extend to a larger area certain concepts and procedures for augmenting precipitation from orographic clouds in the Colorado River Basin and (2) to provide background information to extend the technology. It is important for the accomplishment of the first objective that certain evaluation procedures be stated in advance. These were stated in the Interim Report (Appendix A) and in subsequent materials provided to the Bureau of Reclamation in reports and correspondence and are summarized in this report. It is important for the accomplishment of the second objective that imaginative evaluations be carried out to take full advantage of not previously available data from an extensive seeding experiment. This section specifies some of the evaluations that should be undertaken and suggests others that should be considered.

1. Evaluation Objectives

The Project objectives form the basis for the evaluation objectives. More specifically, the Pilot Project hypothesis is that: (1) a physical model which describes modification potential in terms of wind conditions that control orographic cloud and seeding processes and in terms of cloud temperature structure is basically correct; (2) a modification potential exists when "average" orographic cloud top (or 500 mb) temperatures are warmer than about -24°C (700 θ_e criteria can also be used); (3) increases in overall precipitation of the general magnitude determined for the Climax and Wolf Creek experiments are feasible; (4) operational efficiency using ground generators is adequate to achieve a high percentage of the possible precipitation increases; (5) the cost of weather modification makes it one of the "least cost" alternatives for augmenting water supplies in the Colorado River Basin; and (6) adverse social-environmental impacts are not critically large. The testing of these specific hypotheses should be the basic objective of the evaluation.

2. Evaluation Procedures

The evaluation will require both statistical and physical analyses.

a. Statistical Analyses

The testing of the economic goal of the objective, namely, an increase in precipitation at the ground and changes in streamflow, will require statistical testing. Both non-parametric and parametric procedures are suggested. Each of these procedures should be applied to various meteorologically defined partitions of precipitation in order to empirically obtain insight into physical mechanisms affecting modification processes. Obvious partitions which might be employed include wind directions and velocities at different elevations, cloud temperatures, moisture content indicators, background counts of ice nuclei available at a specified temperature, and combined partitions of these and others. All of these analyses should be accomplished for reasonable groupings of precipitation stations according to similar elevation, spatial and exposure criteria. Principal component analyses at Climax (Mielke et al, 1972) indicate that a single precipitation station describes a given exposure very adequately. The inclusion of additional stations in a grouping (using the mean) improves the precipitation description to a minor extent and is principally beneficial in reducing lost data cases when individual stations are missing.

1. Non-parametric Procedures

The choice of any test should be based on its ability to efficiently detect scale changes induced by a treatment such as seeding. A large class of non-parametric tests termed A_{Nr} tests have recently been discussed (Mielke, 1972). The choice of A_{Nr} test (which include the well known two-sample Wilcoxon and sum of squared ranks tests as special cases) should be based on how well a particular set of precipitation data is described by a distribution for which a specific A_{Nr} test is optimum in detecting small scale changes. Procedures to implement the suggested association between precipitation data and A_{Nr} tests are available (Mielke, 1973; Mielke and Johnson, 1973a).

2. Parametric Procedures

Likelihood ratio tests based on distributions which describe precipitation data reasonable well should be utilized. Four distinct approximating distributions which provide good descriptions of the positive precipitation amount data associated with this study include the log-normal, gamma, beta-κ and beta-P distributions (Mielke and Johnson, 1973b), an adjustment needed in these procedures to account for the proportion of experimental units having zero precipitation amounts is contained in a previously mentioned density function (Mielke et al, 1970) given by

$$f_i(x) = p_i I_{[0]}(x) + (1-p_i) g_i(x) I_{(0,\infty)}(x)$$

where i = 1 and 2 designate a non-seeded and seeded state, respectively, p_i designates the proportion of time that precipitation did not occur during an experimental unit, $g_i(x)$ is the probability density function of precipitation amounts associated with the experimental units having positive precipitation amounts, and the functions $I_{[0]}(x)$ and $I_{(0,\infty)}(x)$ are merely indicator functions given by

$$I_{[0]}(x) = \begin{cases} 1 & \text{if } x = 0 \\ 0 & \text{if } 0 < x < \infty \end{cases}$$

and $$I_{(0,\infty)}(x) = \begin{cases} 1 & \text{if } 0 < x < \infty \\ 0 & \text{if } x = 0 \end{cases}$$

The latter density function together with known techniques for obtaining maximum likelihood estimates of parameters associated with the four previously mentioned approximating distributions for the probability density function $g_1(x)$ (Schickendanz and Krause, 1970; Mielke and Johnson, 1973a, 1973b) yield likelihood ratio test procedures for analyzing possible differences between the non-seeded and seeded precipitation amounts. Of interest is the suggestion that among the four distributions in question (log-normal, gamma, beta-κ, and beta-P), the commonly used gamma distribution may be the poorest of these four distributions in its ability to fit raw positive precipitation amount data (Mielke and Johnson, 1973b). Bivariate response analyses for evaluating target and control area streamflow data (including historical period data) are well known (Wu et al, 1972).

3. Data Samples for Different Objectives

Different precipitation analyses will be required for evaluating (1) the validity of the physical concepts for seeding orographic clouds and (2) the practical modification potential under field operating conditions. These different analyses should consider data samples that include:

(1) Only cases that satisfy the design criteria; i.e., proper winds, cloud temperatures and appropriate seeding operations (This analysis should serve as a test of the physical concepts of modification potential).

(2) All seeded cases including those that were seeded even though cloud temperature criteria were colder than design specifications (This analysis can serve as a test of the practical modification potential for an operations program as carried out in the Pilot Project. It must be remembered that this is a weak estimate of what operational efficiency would be in a fully application-type program since the randomized experiment required a much longer forecast [at least 12-24 hours] for initiating operations).

(3) All events that satisfy the design criteria even though some were not declared as experimental units. (This analysis can be used for a more complete test of practical modification potential that existed during the Pilot Project.) The added events that were not declared experimental must be charged as operational misses or as operational restrictions. Sub-samples for this analysis should separate (1) those cases which were "suitable" but were not declared "experimental" due to "hazard" restriction and (2) those that should have been "experimental" but were not so declared.

b. Physical Analyses

Physical analyses of nuclei concentrations and cloud parameters (ice crystal concentration, shape, size, and riming; radar characteristics; liquid water, etc.) must supplement the statistical analyses. Case studies as well as statistical treatments will be required. Pertinent questions for evaluation are (1) Did the seeding materials consistently arrive in the target (cloud) area in reasonable concentrations? (2) Did changes in cloud ice crystals reflect model considerations (crystal concentrations, size, habit, riming amount, etc.)? These analyses can form the basis for interpreting the reality of the physical model and for making an assessment of the state of development of the technology for application-type programs.

c. Hydrologic and Economic Analyses

Basic objectives of the Pilot Project are evaluation of the quantity of water that might be realized from weather modification and the costs of producing this additional water. One methodology for determining costs is discussed in Section III, C. above and in Appendicies A, Parts E and H, and in Appendix I. For purposes of determining the costs of water production, care will be required in (1) separating true operational costs from those that are related to the research and evaluations aspects of the program and (2) in assigning costs of maintaining a field program that is utilized for operations for only a limited portion of the events with modification potential (since it has research restrictions, i.e., randomization that restricts seeding for half of the events).

The economic analyses will require estimates of the changes in streamflow as determined from the calculated changes in precipitation. One methodology for doing this is described in Appendix H. This involves correlations between high elevation precipitation stations and streamflow. Even though approximately one-half of the experimental events are left unseeded and still other days with modification potential are left unseeded due to operational restriction, serious efforts should be made to evaluate annual streamflow changes using multivariate analyses with non-seeded watersheds for controls. This evaluation can serve as a basic interpretation for project results and also serve to verify the streamflow changes determined from the streamflow precipitation relationships. Evaluation techniques have been explored for the Colorado River Basin by Morel-Seytoux (1971) and Nakamichi and Morel-Seytoux (1971). A specific test designed involves a linear combination of runoff variables with unknown weights. Maximization of power of the test is achieved by the proper choice of the weights, compatible with the constraints of a hydrologic nature.

d. Social-Environmental Consequence Analyses

An additional goal of the Pilot Project is an assessment of the social-environmental consequences of implementing a precipitation augmentation technology. First, second, and third order considerations have been presented in the Interim Report (Appendix A, Part H). Obviously, the detailed analyses of all of these and other impacts are beyond the scope of the Pilot Project. All of these and other potential impacts, however, should be examined and, on the basis of the finding, the more important ones should receive detailed evaluation.

The analyses of social-environmental consequences should not be limited to the target area. Specific attention should be directed to the surrounding and, particularly, the downwind areas. A first effort should emphasize analyses to determine if changes in downwind precipitation may have resulted. With appropriate time-lag adjustments, the precipitation analyses for the target area can also be applied to the downwind areas.

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