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FINAL REPORT

on the

Precipitation Augmentation Potential
by Cloud Seeding in
the State of Utah

by

Geoffrey E. Hill

for the

Division of Water Resources

Salt Lake City, Utah

August 31, 1974

Utah Water Research Laboratory
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1.0 REVIEW

In this report the potential for precipitation augmentation in Utah by cloud seeding will be assessed. Initially, a review of the physics of cloud seeding will be made. Then the climatology of appropriate meteorological conditions will be presented. Finally, the potential for effective cloud seeding in Utah will be given.

1.1 Physics of Cloud Seeding

There is a wide variety of meteorological phenomena which may be modified artificially. In some instances modification may take place inadvertently; but here we are concerned only with planned modification activity. It might be expected that besides increasing precipitation, we might be able to decrease it at times, or we might reduce hail and lightning. In each of these situations the prime opportunity available for manipulation is the number of nuclei present in the atmosphere. In the natural atmosphere tiny particles are usually present upon which water or ice collects. Of course, some atmospheric disturbance must be present in order to provide the vertical lift of air required to produce visible water.

A further limitation on available opportunities to change the natural conditions, is that nuclei can only be added. If nature has already provided an overabundance of nuclei in the atmosphere, there is little that can be done. (In the future there may be ways found to reduce the number of effective nuclei, but this is an unexplored area.)

Nuclei of condensation or sublimation comprise a wide variety of substances. Nuclei of condensation are usually some kind of hygroscopic liquid.

Water will begin to collect on such a nucleus even below saturation. Nuclei of sublimation, or ice nuclei, are usually solid particles having some similar physical characteristics as found in ice. Dry ice (frozen CO_2) or silver iodide (AgI) are the most common substances used.

One facet of weather modification activity is the mode of delivery of artificial nuclei into a cloud. To distribute seeding material into a cloud it is released in a variety of ways depending upon the nature of the cloud system and the cost. The number of nuclei required for effective seeding of a small winter storm for a period of an hour or two is in the trillions. To distribute this number of particles evenly over a storm system is virtually impossible.

1.2 Storm Types and Cloud Seeding Technology

1.2.1 Basic concepts. A broad classification of storms could be made by separating them into stratified clouds or convective clouds. Stratified clouds are those covering distances of several hundred miles and are of a relatively uniform structure. Such storms are typically found in the winter. On the other hand, convective storms are those covering distances of only a few miles and are readily identified with thunderstorms typical of the warmer months. These two storm types often occur together; there may not be thunderstorms present in such mixed types, but winter stratified clouds may occur with strong convective characteristics.

Because the expected response to cloud seeding is strongly dependent upon the basic cause of the cloud formation as well as the cloud type, a further classification of storms is required. There are seven main types: convection, orographic convection, cold fronts, squall lines, winter cyclones, winter orographic clouds, and tropical cyclones (hurricanes). In Utah the most

frequent types are winter orographic, convection, orographic convection, cold fronts and to a lesser extent, winter cyclones.

During winter when moisture-bearing winds blow across a mountain range, water condenses to form clouds. Some portion of the cloud reevaporates on the downwind side. When the cloud temperature is low enough so that natural ice nuclei convert cloud droplets to snowflakes as fast as condensation supplies the water, natural precipitation efficiency is high. Addition of artificial ice nuclei will tend to produce more but smaller snowflakes; more of them will blow across the range without falling on it, and snowfall will be displaced downwind and perhaps decreased. But if the clouds are not cold enough for natural ice nuclei to do the whole job, then addition of artificial nuclei will increase the precipitation efficiency. If the temperature is too warm, even artificial nuclei will be ineffective.

The "window" for effective treatment is therefore framed by (a) weather events that produce substantial condensation over the mountains, (b) in-cloud temperatures within a particular range determined by the activation of natural and artificial ice nuclei and the rate of growth of the resulting snowflakes, and (c) the extent of dispersion of artificial ice nuclei within the cloud. Computational models take account of these three factors. Field experiments and field observations are more limited.

Dispersal of artificial ice nuclei is affected by availability of seeding sites as well as by variations of the weather. Capability for detailed observation of cloud thickness and in-cloud temperature is restricted. Application of the window concept from one field experiment to another varies accordingly, though the underlying principles remain the same.

1.2.2 Winter orographic cloud seeding. Well over a dozen separate cloud seeding experiments have been conducted in the Western States to increase

precipitation during winter. In general it has been concluded by those conducting the experiments that there is an increase from seeding depending upon a number of meteorological factors. Because some of the experiments were not randomized there may well be a bias in the reported results. Therefore, our attention is directed to those experiments with randomized seed no-seed programs.

In the Santa Barbara Project, Elliot et al (1971) reported the successful treatment of convection bands. Although no overall significance level was given, half of the reporting stations showed increases of 50 percent or more with significance at the 5 percent level. The increases reported depended upon the temperature lapse rate, the height of release of silver iodide and the cloud temperature. These results were obtained using a target-control method of evaluation. A total of 85 convective bands were examined.

The Pacific Gas and Electric Company has carried out a project (Lake Almanor) for several years. Mooney and Dunn (1969) have reported the results obtained over a five year period. Seeding was carried out with six automatic silver iodide generators located atop ridges or peaks. Precipitation amounts were recorded at 49 locations within a target and control area. Radar and upper level soundings were also utilized. Four categories were designated according to whether the temperature was warmer or colder than -5°C at 7500 feet and whether the upper wind was southerly or westerly. The cold westerly category showed increases in seeded precipitation of about 32 percent. The significance level was reported at the 5 percent level.

It should be noted that when data are divided up into various arbitrary categories the chance of finding an apparent effect increases according to the number of categories. Furthermore, the physical basis of an increase in

precipitation from seeding in the cold westerly category compared to the others, is questionable.

A seeding program called Project Skagit was carried out in Washington during the two winters from 1962-1964. According to comparisons with historical regression operations the runoff on the Skagit River was enhanced 5 percent and 15 percent during the two years. No randomization or meteorological "windows" were utilized in this program.

In Colorado a ten year randomized cloud seeding program (Climax Experiment) was carried out by Colorado State University. The time unit was 24 hours and the criteria for seeding was that .01 inch of precipitation was expected at Leadville, Colorado and the 500 mb wind direction was 210° through 360° inclusive. Randomization was employed in the experiment, but the randomization was restricted to large blocks (around 20 or 30 cases) such that each block contained the same number of seeded and nonseeded cases. Data were examined for various stratifications of upper level temperature and wind. The most significant result is that seeding effectiveness displayed a strong dependence on temperature. When the 500 mb temperature was between -11°C and -20°C , increases of around 75 percent occurred. In other temperature categories either a small positive or a small negative effect was found.

The results of this project have been regarded by the scientific community as being probably the most credible cloud seeding experiment on winter orographic clouds. For example, the National Academy of Sciences' (1973) report on Weather and Climate Modification states that the Climax experiment shows "the contribution to the overall winter precipitation to be 10 to 30 percent when only those cloud systems having cloud temperatures in the range of -11°C to -20°C are seeded. Hence, in the longest randomized

cloud-seeding research project in the United States, involving cold orographic winter clouds, it has been demonstrated that precipitation can be increased by substantial amounts on a determinate basis." On the other hand, a renowned cloud physicist has reacted to the NAS report in a review published by the World Meteorological Organization.

Dr. B. J. Mason states that "when the National Academy of Sciences of the United States commissions a panel of senior and well-known scientists to prepare a report on a scientific activity of national and international importance and concern, one expects an objective, critical, closely-argued assessment of recent developments leading to balanced, unbiased judgements pointing the way to future action. Such a review is badly needed in the controversial field of weather and climate modification, where extravagant claims are regularly made and often denied, if only because many developing countries suffering from drought or devastating storms wish to explore any reasonable chance of successful intervention but need guidance in a confused situation in which professional opinion is much divided, not least in the United States. Unfortunately this superficial, uncritical, inflated and badly constructed report, whose conclusions are not supported by any real analysis or argument, fails completely to meet this need." Dr. Mason further comments that "no project, practice or hypothesis is directly criticized or judged unprofitable; nearly all appear promising and are commended for further investigation." Unfortunately the foregoing statements reflect a general condition in which the field of weather modification is embedded. However, the field is not without numerous scientific efforts which have contributed important and sometimes crucial findings in weather modification technology, but not necessarily a promise of precipitation increases.

Some specific criticisms of the Climax result are as follows: One of the criteria for a seedable event is that .01 inch of precipitation is expected in a 24 hour period. This weak criterion leads to a large number of cases with little or no precipitation. When there are a relatively few events having heavy precipitation, the results are dominated by those cases. Another weakness in the analysis is that all types of events are included: orographic, cyclonic, convective and frontal cases. Thus a few outstanding disturbances with different physical characteristics may dominate the results. Still another important shortcoming of the analysis is that the 500 mb temperature is used as a basis for inferring the cloud top temperature. This inference is a necessary step in order to provide a physical basis for the expected result, but in fact the 500 mb temperature is likely to be only moderately well correlated with the actual cloud top temperature.

A large number of additional experiments have been carried out by the Bureau of Reclamation under its Skywater Project. These projects include the large, diverse Colorado River Basin Pilot Project. To date no firm evidence of cloud seeding effectiveness has been detected. The experiment is continuing and results may yet be forthcoming. The Bureau of Reclamation has sponsored other projects involving cold orographic winter cloud seeding. These are operated by Fresno State College Foundation, Montana State University, New Mexico State University, Utah State University, University of Washington, and Aerometric Research, Inc. These projects can be reviewed in the Annual Reports of Project Skywater published by the Bureau of Reclamation. Most of these projects have found increases in precipitation of 50 percent or more under certain meteorological conditions, usually similar to those found in the Climax experiments. However, one is best cautioned an accepting at face value the various results claimed.

Little of this work has been subjected to publication review, and virtually none of the projects have been subjected to a complete project review by independent parties. (Such a procedure is evidently badly needed to sort out the true potentialities of weather modification.)

1.2.3 Summer convective cloud seeding. For summer-convective precipitation, the time available for growth of precipitation particles is basic to the window concept. When convective ascent of air produces clouds, the lifetime of an individual cloud parcel is related to the speed of the updraft and the height to which the cloud summit rises before the cloud disintegrates, usually because of admixture with drier surrounding air. Large condensation nuclei enter the cloudbase, grow slowly at first by condensation, then progressively more rapidly by accretion, which may be by a liquid drop collecting smaller cloud droplets until it grows large enough to break up and generate a burst of new drops. A second process involves a frozen particle collecting cloud droplets in the form of rime ice, forming snow pellets or hailstones that do not break up until they melt. The great majority of convective clouds fail to produce precipitation because the lifetime of air parcels within them is shorter than the growth time of precipitation particles.

Seeding a cloudbase updraft with large hygroscopic nuclei shortens the time before precipitation appears, and permits precipitation to form in a shallower cloud than it would naturally. Removal of water in the rain shaft lightens the cloud and increases its buoyancy, hence both the height to which it rises and the lifetime of yet other cloud parcels within it increase. Furthermore, with less water to evaporate at the cloud margins, there is less cloud-killing cooling during the late-mature phase to hasten disintegration of the cloud. However, evaporation of artificially stimulated

precipitation beneath the cloud may reduce available buoyancy prematurely.

Seeding a cloudbase updraft with ice-forming nuclei produces rudimentary precipitation particles in the supercooled portion of the cloud (above the freezing level) at a warmer temperature and hence sooner than they would form by natural freezing processes. This shortens the time needed to get the precipitation process going in those clouds in which the all-water process is slow initially. The ice-forming nuclei also release latent heat, making the cloud more buoyant so that it rises higher. Ice particles may grow after they reach a certain size by accretion of cloud droplets and become snow pellets or hailstones. On the other hand, the added buoyancy may increase the updraft speed so much that the lifetime of the cloud parcel is shortened. In this event, the protoprecipitation particles may be thrown out of the top of the cloud before growing large enough to fall all the way to the ground. Under such conditions, the effect of seeding may be to shorten the time available for precipitation growth and result in decrease of precipitation at the ground while increasing the amount that drifts off as cirrus clouds at very high altitudes.

Different combinations of these effects correspond to "windows" for precipitation increase, or to "windows" for precipitation decrease, depending upon whether the combined effect is to increase the growth rate of particles or increase the duration of their stay in precipitation-growing regions of the cloud, or vice versa.

Analysis of randomized seeding experiments by the South Dakota School of Mines and Technology group showed that, for both hygroscopic and ice-phase seeding, the effect is greatest on cumulus clouds that do not attain great size. This is interpreted to mean that seeding has little effect on clouds that naturally provide a long cloud-parcel lifetime for development

of precipitation. In unseeded clouds nearer the borderline of natural precipitation capability, precipitation did not appear until the upmoving parcels had attained a certain age. In clouds seeded with ice-forming nuclei, the height of first precipitation formation was related most closely to the cloud-base temperature, suggesting that precipitation particles formed quickly once the effective temperature of the seeding agent had been reached. In clouds seeded with hygroscopic nuclei, the first precipitation formation tended to occur at a more or less constant height of about 1.6 km above cloudbase, suggesting that the seeded cloud formed precipitation quickly once a critical quantity of condensation was exceeded, regardless of temperature.

In the case of orographic convection the clouds are often found only in selected areas, usually not far from a strongly heated sloping mountain side. These clouds frequently develop into large rain-producing cumulus or thunderstorms, while in nearby flatlands there may be a complete absence of clouds. The physical characteristics of orographic convective clouds are apt to be very similar to ordinary convective clouds. In the former, the region of initial development is tied to the topography, but with further development the clouds may move away from the generating region. Therefore, there are likely to be very large spatial variations of natural summertime precipitation in mountainous regions. Long term averages of summer precipitation near mountains may be highly dependent upon the precise location of rain gages. However, it is within the framework of existing knowledge to formulate models to describe long term averages of summer precipitation.

Other important sources of precipitation in Utah are the passage of cold fronts and the occurrence of cyclonic disturbances. Cold fronts

crossing Utah are associated with cyclonic disturbances; usually the paths of these low pressure centers cross Idaho and the cold fronts trail southward or southwestward into Utah. These fronts usually have strong convective characteristics, and when in the vicinity of mountains there is a strong orographic component. As these storm systems move eastward substantial precipitation falls for several hours. Occasionally a cyclonic disturbance will move through or south of Utah, in which case widespread precipitation may occur. Very little is known about the effects of seeding either cold fronts, especially in mountainous terrain, or cyclonic disturbances. It is probable that there is a large amount of ice present in such long lasting cloud systems, especially when these clouds extend upward to very cold temperatures, as they usually do. On the other hand when these storms contain strong updrafts, or when strong updrafts are generated in the vicinity of mountains, a greater amount of supercooled water may be produced than either the available ice nuclei or ice crystals falling from above can convert to precipitation-size particles. In fact in mountainous regions there may exist selected regions where ice crystals at higher altitudes cannot penetrate the updraft where new supercooled cloud-water is being generated. This situation, of course, constitutes an opportunity for artificial cloud seeding.

1.3 Relationship Between Clouds and Precipitation

To assess the potential for precipitation augmentation by cloud seeding, consideration must be given to the frequency and location of cloudiness. Furthermore, the type of cloud and its temperature are important factors to consider in a seeding program.

Unfortunately there is very little available data on the climatological structure of clouds. Although there is a fairly large body of data on

cloudbases in a few locations in Utah, there is little information on the vertical extent of clouds. In mountainous regions, especially at high elevations, there is virtually no data on cloud frequency and vertical extent. Because much of the precipitation in Utah either occurs in or is initiated by high mountains, another means of assessing the potential for precipitation augmentation must be devised.

What is usually given as a substitute for cloud data is precipitation data. It is inferred that the cloudiness is directly related to precipitation. What is often used as a measure of the potential artificial-increase in precipitation is the precipitation itself and some percent of that amount. For example, with winter orographic precipitation, increases of around 20 percent are often quoted. If 10 inches of precipitation occur in winter at a mountain locality, then an increase of 2 inches would be expected by cloud seeding if a 20 percent figure were used. Such juggling of figures may lead to interesting dollar values, but there are large uncertainties involved.

The assumed direct relationship between the amount of added precipitation and the precipitation itself is somewhat questionable even assuming the cloud temperature conditions are suitable. Much of the wintertime precipitation, for example, is caused by cold frontal systems which may have a rather different response to cloud seeding from purely orographic clouds. Some proponents of cloud-seeding technology believe that cloud systems just on the verge of precipitating provide the greatest potential for artificial increases. Yet it may be argued that the frequency of such situations is proportional to the seasonal average amount of precipitation.

2.0 ANALYSIS OF PRECIPITATION AUGMENTATION POTENTIAL IN UTAH

2.1 Geographical Distribution of Precipitation

The geographical distribution of precipitation in Utah is separated into two basic regimes, the summer and winter distributions. Within each of these seasons there are significant variations which need to be taken into account. In Utah there is a close relationship between precipitation and elevation. In the winter the relationship is founded upon the orographic lifting of moist air. In summer the basis of the relationship is the more strongly heated sloping mountain sides compared to the surroundings.

Because the clouds and precipitation pattern are tied so closely with the (fixed) topographical features, cloud seeding may be carried out effectively with relatively inexpensive ground based generators. Furthermore, generators may be placed on mountain tops or other special locations where the seeding material would be readily incorporated into the clouds. Another possibility for effective seeding is to use tethered balloons. Although such a means of delivery is not common, the same advantages as described above for ground generators would apply. In addition, use of tethered balloons would assure that seeding material entered the clouds and not become trapped near the surface. Another advantage of tethered balloons is that a much greater flexibility in possible release sites would be achieved compared to available locations for ground generators. However, for large statewide projects the use of fixed ground generators is preferred.

To find the distribution of precipitation in Utah over particular periods of interest and to assess the consequences of year-to-year variations as well as variations within a season, data from twenty-eight precipitation stations listed in Figure 1 have been analyzed. These stations were selected out of some 278 according to several criteria. Both a wide distribution of stations over the State and stations with records of at least fifty years are desired. Also, adequate representation of high altitude locations is important. The geographical distribution and regional designation of the selected stations are given on the map shown in Figure 2.

Data from these twenty-eight stations were punched on IBM cards and a computer program was written to describe monthly and regional variations. In addition, correlations between precipitation from each of the stations were made. From this data the monthly or yearly variations in precipitation augmentation potential can be derived.

Because the meteorological conditions required for positive seeding effects during winter are normally found from November through March, the winter season will be designated accordingly. Thus, the winter precipitation shown in Figure 3 is limited to these months rather than the longer period often used in hydrological studies. In this figure values obtained from data utilized are plotted at the station location. Analysis of precipitation amounts at other locations is made on the basis of precipitation versus elevation relationships, other physiographic features, and general meteorological principles.

It is clear from Figure 3 that there is almost twice as much precipitation in the north compared to the south for the same elevation. However, there are large areas both north and south where both the precipitation and the elevation are large. Thus, it is well known that spring

<u>No.</u>	<u>Name</u>	<u>Elevation</u>	<u>ID</u>	<u>Years of Record</u>
01	Silver Lake	8740	SL	58
02	Hiawatha	7280	HW	57
03	Hatch	6900	HT	58
04	Logan	4785	LG	73*
05	Ogden	4330	OG	73*
06	Utah Lake	4497	UL	69
07	Elberta	4690	EL	72
08	Nephi	5240	NP	68
09	Levan	5315	LV	73*
10	Salina	5190	SA	50
11	Tooele	5070	TL	73*
12	Oak City	5075	OC	69
13	Deseret	4585	DS	73*
14	Milford	5028	ML	66
15	Modena	5460	MD	73*
16	Wendover	4237	WN	62
17	Callao	4330	CL	35
18	Laketown	5988	LK	73*
19	Woodruff	6315	WD	72
20	Castle Dale	5660	CD	73*
21	Emery	6250	EM	73*
22	Escalante	5810	ES	72
23	Mytan	5030	MY	58
24	Fort Duchesne	4990	FD	73*
25	Jensen	4720	JN	58
26	Thompson	5140	TH	62
27	Moab	3965	MB	73*
28	Bluff	4315	BL	62

*Additional data prior to 1901 is available.

Figure 1. Precipitation stations, elevations, and years of record

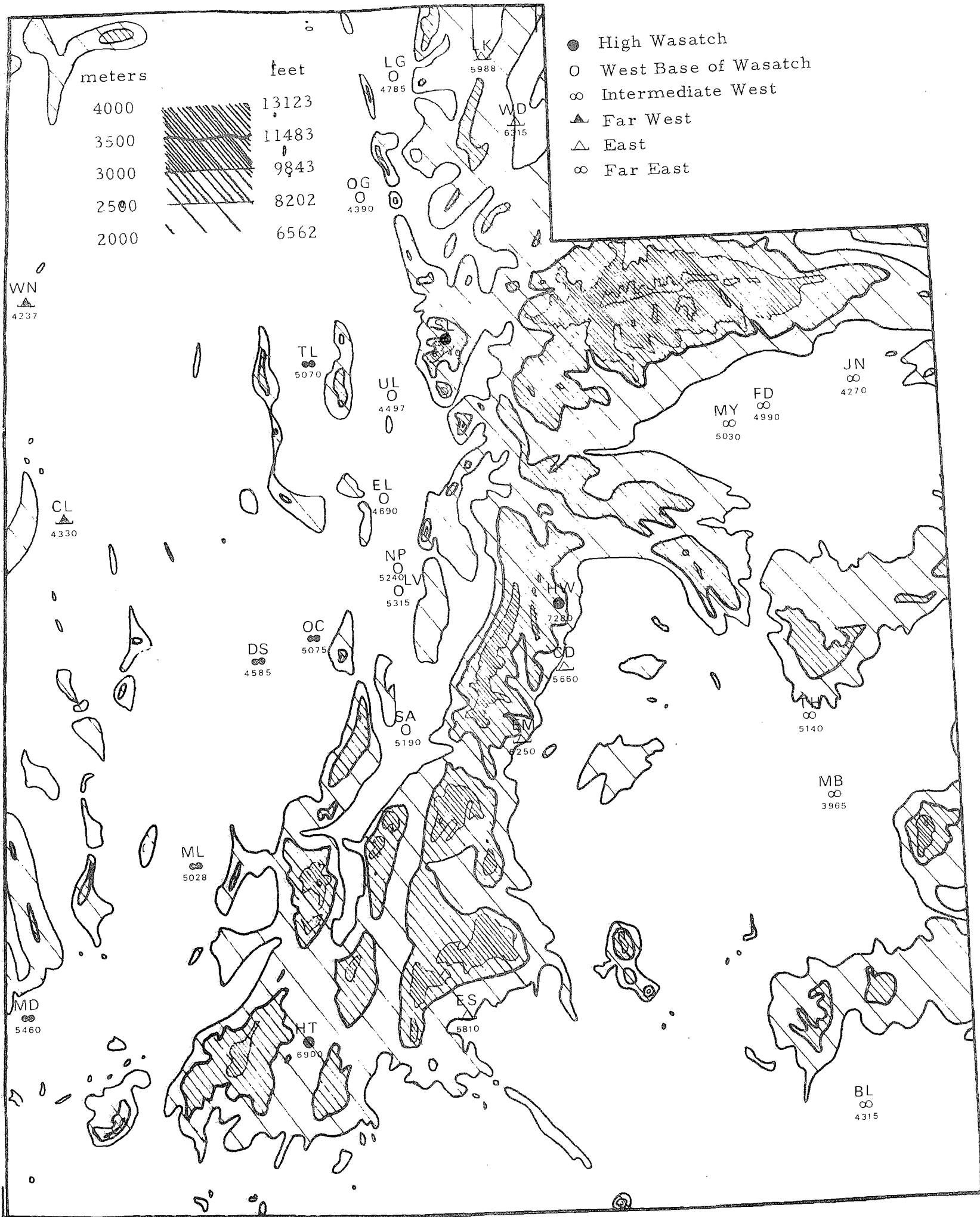


Figure 2. Precipitation stations and elevations (ft. above msl).

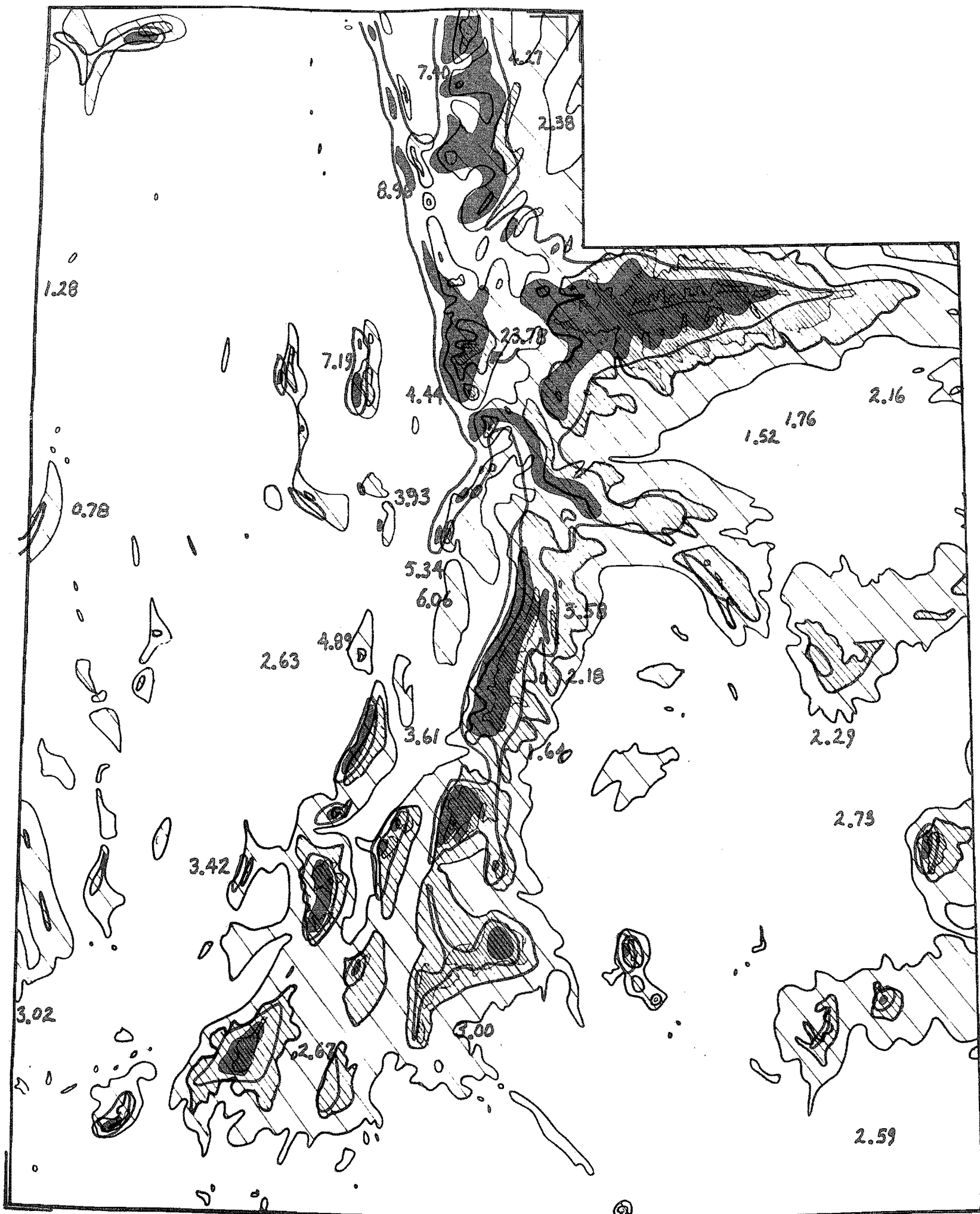


Figure 3. Median winter precipitation (November through March). Shaded areas above 15 inches; contours, 10 inches; and numerical values in inches.

runoff is available to agriculture and other activities requiring large amounts of water. However, there is one aspect of the yearly cycle that has received relatively little attention, at least in terms of its relevance to cloud seeding. This factor is the variability of winter amounts from year to year. The related question is whether a cloud seeding program could be depended upon even if the cloud seeding effects were precisely known. Because the storage of water associated with spring runoff is found at high elevations, the year-to-year variations in winter precipitation are examined using Silver Lake Brighton data. Here the elevation is 8740 feet and a 57 year record is available.

At Silver Lake the median precipitation is 23.84 inches with a standard deviation of 4.76 inches. The lowest winter snowfall (5 months) occurred in 1931 with 11.57 inches; the next lowest occurred in 1926 with 16.17 inches. Thus, there is a fairly reliable source of water in the higher elevations during winter.

For the geographical distribution of summer precipitation, data are presented on monthly charts, the reason being that large variations occur in the pattern of summer precipitation as the season progresses. In June (Figure 4) the greatest precipitation occurs in the north over elevated terrain. In July (Figure 5) the greatest precipitation occurs in the south especially over higher elevations. Precipitation in the north is less than in June, but not greatly less. In August (Figure 6) precipitation is greatly increased in the south especially near and in mountains. In the north precipitation is comparable to that found in July.

To assess the reliability of summer precipitation the minimum precipitation for the combined months of June and July was found for the precipitation stations over the period of record; these values are shown

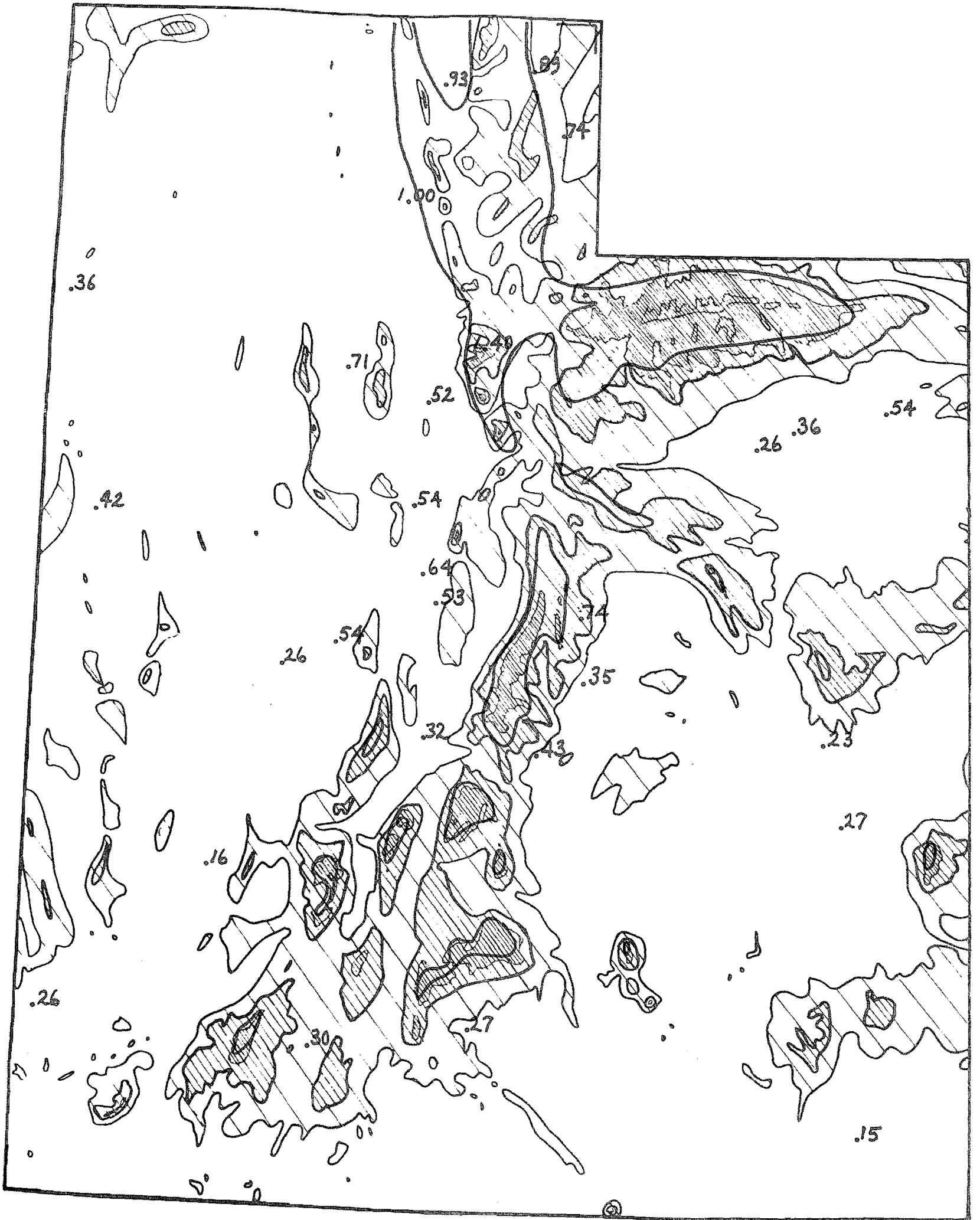


Figure 4. Median June precipitation. Contours, 1 inch; numerical values in inches.

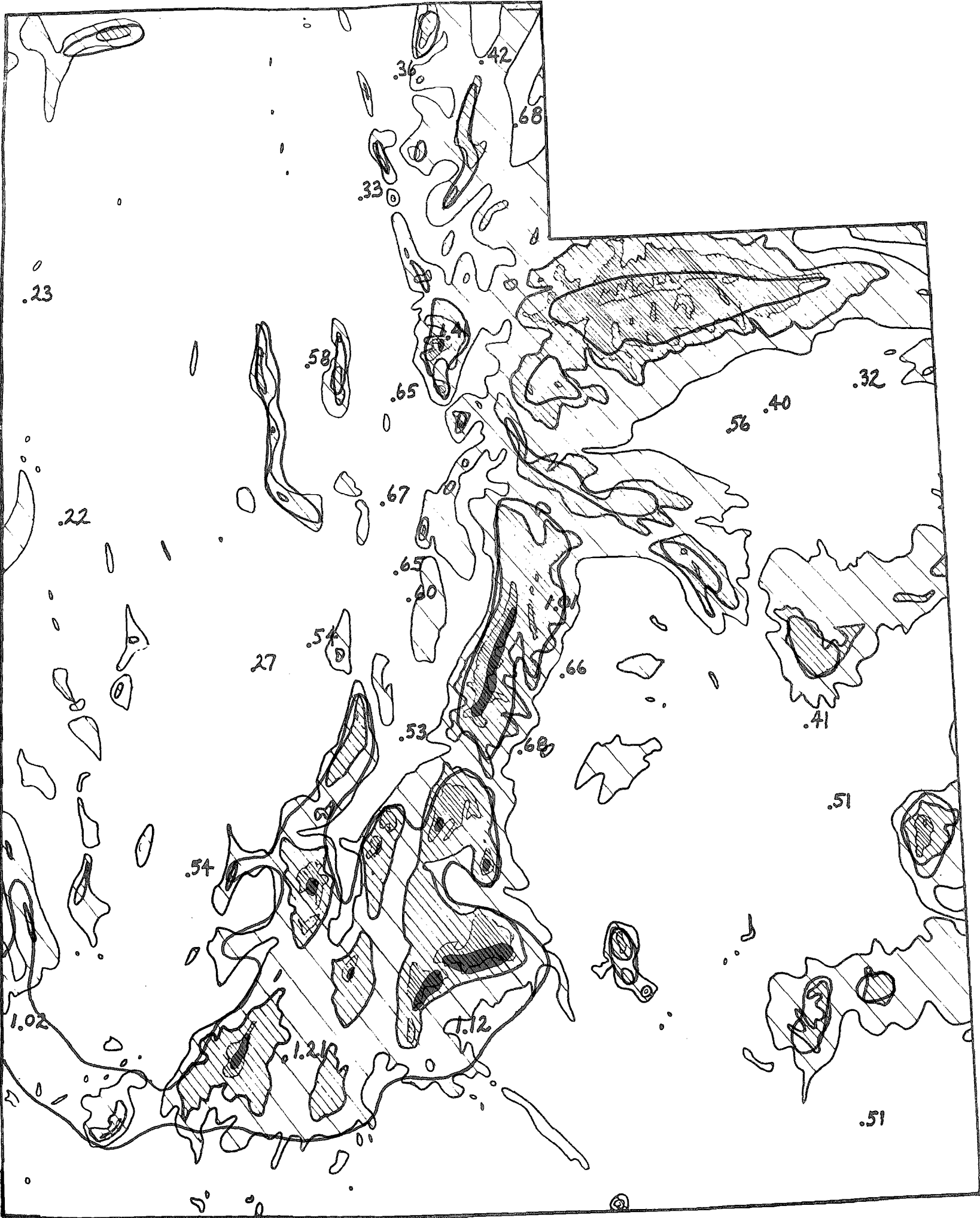


Figure 5. Median July precipitation. Shaded areas above 2 inches; contours, 1 inch; and numerical values in inches.

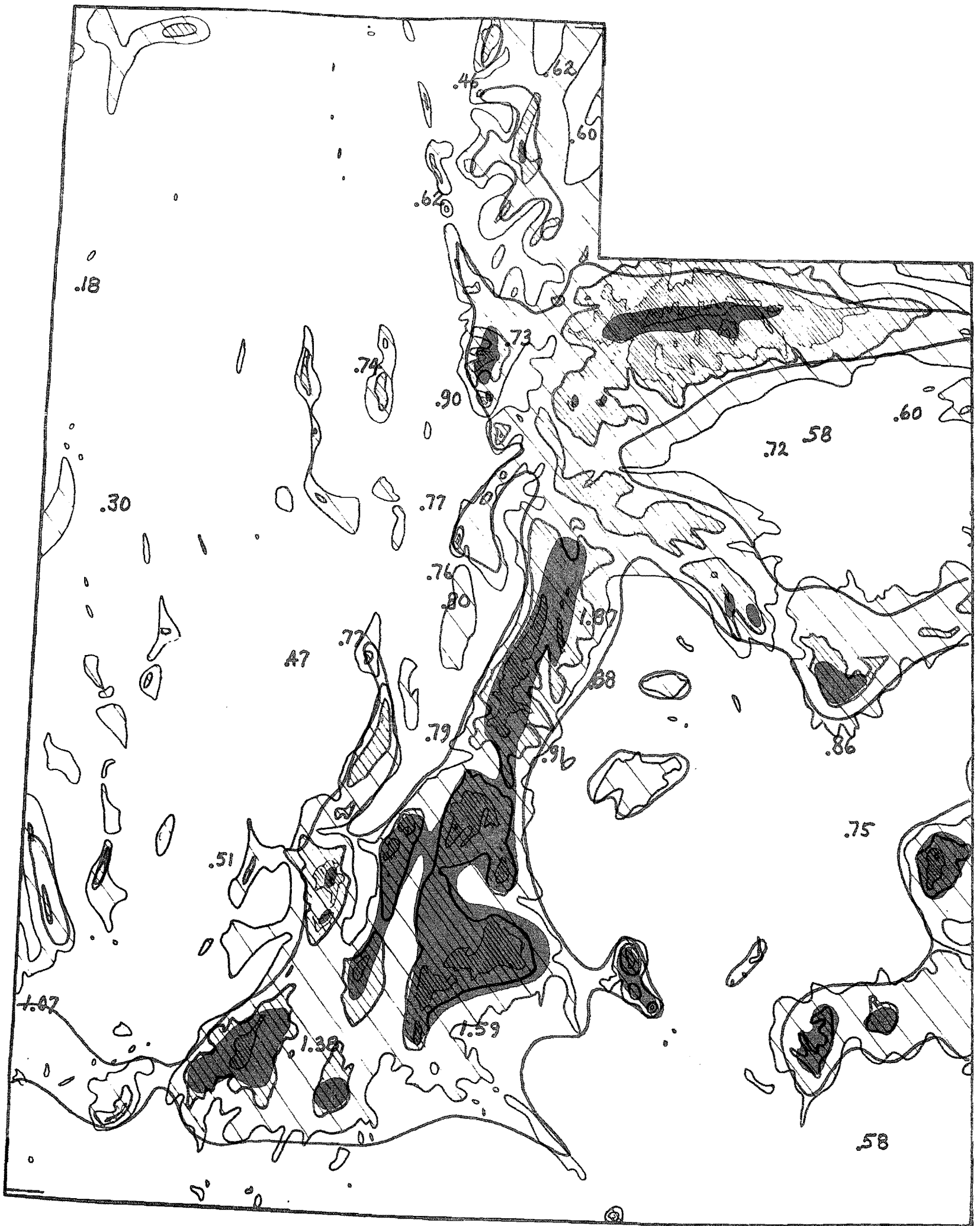


Figure 6. Median August precipitation. Shaded areas above 2 inches; contours, 1 inch; and numerical values in inches.

in Figure 7. It is clear from this figure that the minimum precipitation approaches zero for these two months. Further examination of data from Ogden (north) and Escalante (south) showed the frequency of serious summer droughts. From 1917, which is the start of the Silver Lake record, the five lowest amounts of June-July precipitation averaged 0.19 inch at Ogden and 0.25 at Escalante. These amounts represent 10 percent and 18 percent of the median June-July amounts, respectively. On the other hand, the five lowest winter amounts at Silver Lake averaged 68 percent of the median. Furthermore, all but one of the low winter amounts occurred in different years than the low summer amounts. Unfortunately, during the one year of both low winter and summer amounts, the lowest of all winter amounts was recorded. This year, 1931, must have been an all around disaster.

2.2 Cloud Seeding Opportunity Recognition in Utah

Although precipitation amounts may provide a basis for estimating either the frequency of storms or the occurrence of extensive cloudiness, there still remains the problem of how effective a seeding treatment will be in a particular case. In winter the critical factor is the concentration of ice crystals naturally present. Laboratory work and field observations suggest that there are fewer ice crystals present at temperatures warmer than about -22° C than is normally required for efficient precipitation. Thus, to recognize a seeding opportunity in winter we need only assure ourselves that the coldest temperature, nearly always found at the cloud top, is warmer than about -22° C. The upper limit for effective cloud seeding is believed to be around -12° C.

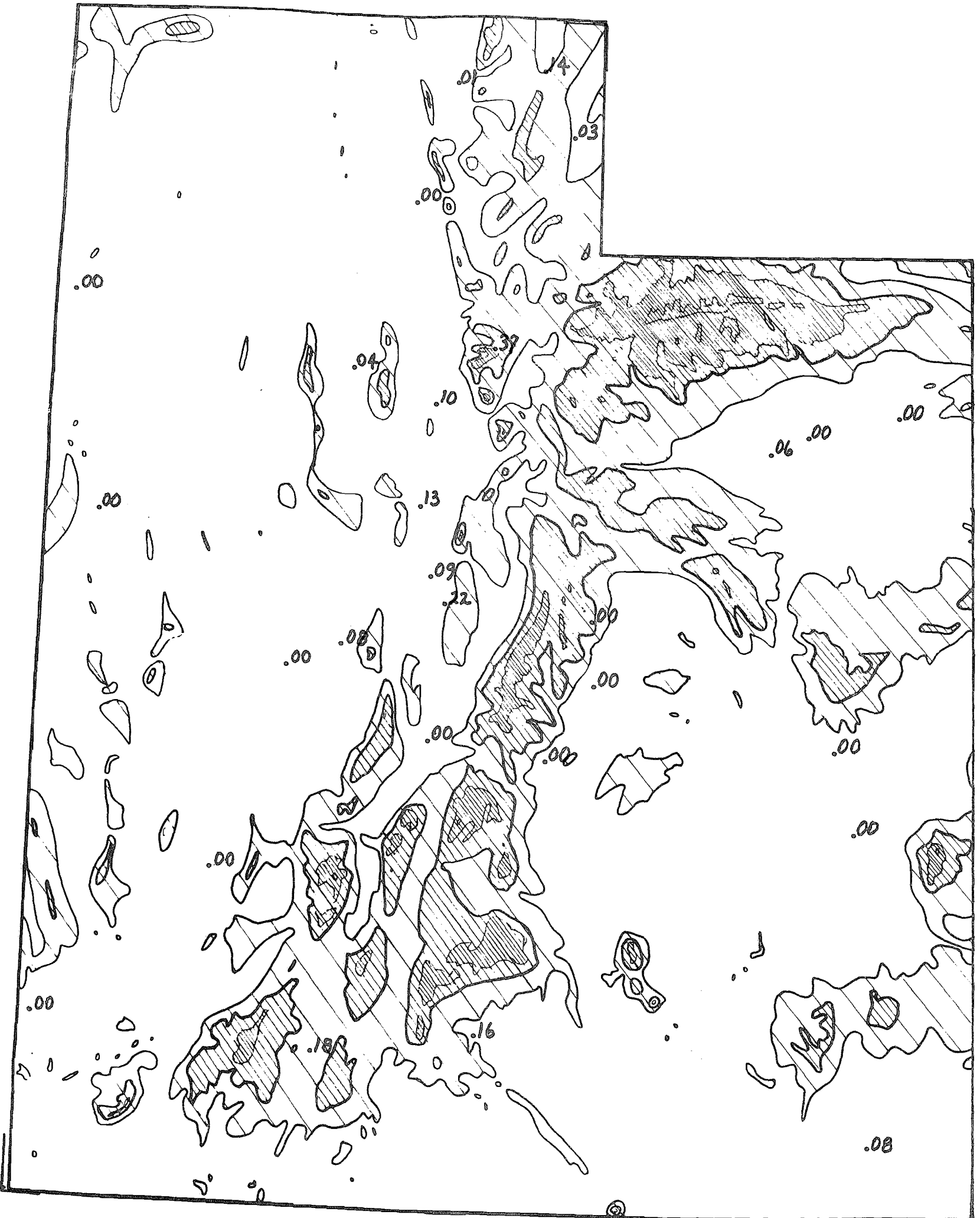


Figure 7. Minimum June-July precipitation (approximately 60 years), in inches.

In Utah during summer the dominant mechanism for the growth of precipitation-size particles is, as in winter, the collection of super-cooled cloud droplets onto an ice crystal. However, it is very difficult to ascertain the cloud top temperature, because the clouds extend horizontally only a few miles and the height may vary greatly from cloud to cloud. Furthermore, the spatial variation of convective clouds is very great. For these reasons it would be worthwhile to devise a simple means of collecting convective cloud data on a regular basis. As pointed out in the previous section, the use of numerical models is being made to assess the rather complicated set of circumstances in which seeding of convective clouds might be effective.

For the foregoing reasons, analysis of cloud top temperatures appears to be useful only for winter orographic clouds. For this situation analysis has been made of upper level soundings taken at the Salt Lake City Airport when precipitation was occurring at Silver Lake Brighton. From the upper level soundings, estimates may be made of the cloud top temperatures. Although in any one instance, the estimated temperature may be in error by several degrees, the use of ten years' data should give a good picture of the frequency of appropriate seeding conditions.

According to simple theory, there is an opportunity for effective seeding when the cloud top temperatures are between about -12° C and -22° C. If we use a criterion adopted by some researchers, i. e., that cloud tops are found when the relative humidity drops to 80 percent as one proceeds upward, then seeding could be carried out during 60 percent of the total precipitation. However, it is probable that in many of the cases where the relative humidity is 80 percent the cloud is in fact

composed primarily of ice, and that the relative humidity with respect to water in the cloud may be very close to 80 percent. Such ice clouds are, of course, not seedable if an increase in precipitation is desired. Recent work at the Utah Water Research Laboratory suggests that about half of the clouds falling into the so-called seedable window according to the 80 percent relative humidity criterion actually extend to much higher altitudes and colder temperatures, and contain large amounts of ice crystals. Therefore, a value of 30 percent for the seedable fraction of precipitation is probably closer to the true picture than is a value of 60 percent.

For more southerly parts of Utah the fraction of storms with appropriate cloud top temperatures is about the same as at Salt Lake City. Although the temperatures are typically a few degrees warmer to the south of Salt Lake City, some events too cold for effective seeding near Salt Lake City would be suitable to the south and some events just cold enough to seed near Salt Lake City would be too warm in the southern part of the State.

In summer, the bulk of precipitation falls from convective clouds which extend to great heights where the temperature is cold enough to produce large concentrations of ice crystals. On the other hand, the average amounts of precipitation probably are well-related to the frequency of smaller clouds for which artificial seeding would be effective. But the actual fraction of seedable clouds and how much precipitation can be increased by seeding are unknown. The following analysis of data from Hill Air Force Base is made in order to make some assessment of seedable fraction of summertime clouds.

Data from Hill Air Force Base over a twenty-two year period show that the hourly frequency of thunderstorms between May and September reaches a maximum in August. In May the average number of hourly reports of thunderstorms is 3.52; in June, 3.99; in July, 3.83; in August, 8.61; and in September, 4.56. Although the cloudbases are generally higher as the summer progresses, there is a sharp peak in the frequency of thunderstorms in August at Hill Air Force Base.

Another measure of summer seeding opportunities is the frequency of precipitation other than thunderstorms. These less intense precipitation events compared with thunderstorms are likely to present favorable seeding opportunities. Hill Air Force Base data show that in May the average number of hourly reports of precipitation without thunderstorms is 41.9; in June, 29.0; in July, 8.9; in August, 9.1; and in September, 18.7. These data reveal a definite minimum in the frequency of events in late July, just the opposite of thunderstorm frequency.

When using precipitation amounts as a measure of the frequency of favorable seeding events, we are obliged to subtract the amounts due to ice-crystal bearing thunderstorms. Although thunderstorms occur relatively infrequent (25 hours) compared to precipitation in the absence of thunderstorms (108 hours), the amount of precipitation from an individual thunderstorm exceeds the precipitation in a non-thunderstorm event by a substantial factor. For sake of discussion we will assume this factor is five. Although a considerable effort would be required to determine the correct value, the basic picture to emerge probably would not be much changed.

The fractional contribution, F , of non-thunderstorm precipitation to the total precipitation is found by the following formula:

$$F = \frac{N_P}{fN_T + N_P}$$

where f is the factor assumed equal to 5, N_T is the number of thunderstorm hours and N_P is the number of non-thunderstorm precipitation hours. Thus, the percent of precipitation, for which seeding is likely to be effective, is for May, 70 percent; for June, 59 percent; July, 32 percent; August, 17 percent; and for September, 45 percent. From the portion of precipitation indicated by these percentages we may expect increases of precipitation. In summer the reported effect of seeding ranges from decreases of about 50 percent to increases of about 100 percent. When convective storms occur over extensive areas the effect of seeding appears to be negative, as would be expected according to our reasoning presented in the foregoing analysis of summer seedability. Otherwise, a positive effect of seeding might be expected.

In summary, we have generated an approximate basis for finding seedable cases in both winter and summer. The actual increase to be realized is the numerical product of the fraction of seedable cases, the total precipitation, and the percent increase due to seeding. The last mentioned factor is not yet very well known. For winter orographic clouds increases of 10 or 20 percent of the total winter precipitation have been frequently quoted. For summer convective clouds of moderate size, increases of an unspecified amount may be expected.

Because the quantitative effects from seeding are still uncertain, our results will be presented in the form of a fixed rate of increase, and these results can be modified as believed appropriate. It will be

assumed that the rate of increase due to seeding of seedable cases is 25 percent in the winter and 50 percent in the summer.

2.3 Precipitation Augmentation Potential in Utah

In the previous sections we have developed an approximate means of assessing the precipitation augmentation potential in Utah for both winter and summer. For both seasons a general formula for the precipitation increase, I , is

$$I = a \times F \times P$$

where a is the fractional increase of precipitation from a seedable cloud, F is the fraction of seedable clouds and P is the total precipitation for a month or a season. In this report the value of a is assumed equal to .25 for winter and .50 for summer. The value of F has been found to be roughly .30 in winter and variable in summer ranging from a maximum of around .70 in May to .17 in August. Values of P are, of course, obtained from long term records throughout the State.

2.3.1 Winter seeding potential. The augmentation of precipitation in Utah during winter is shown in Figure 8. As previously indicated, to increase precipitation only about one third of the precipitation can be seeded. If an increase of 25 percent is assumed, we obtain the result shown. The largest increases are confined to the highest elevations. Typically, increases of an inch or more are found at elevations above about 7000 feet in the northern Wasatch and above about 10,000 feet in the Uintas and southern Wasatch. It is in such high elevations that the source of spring runoff exists. Thus, whatever the

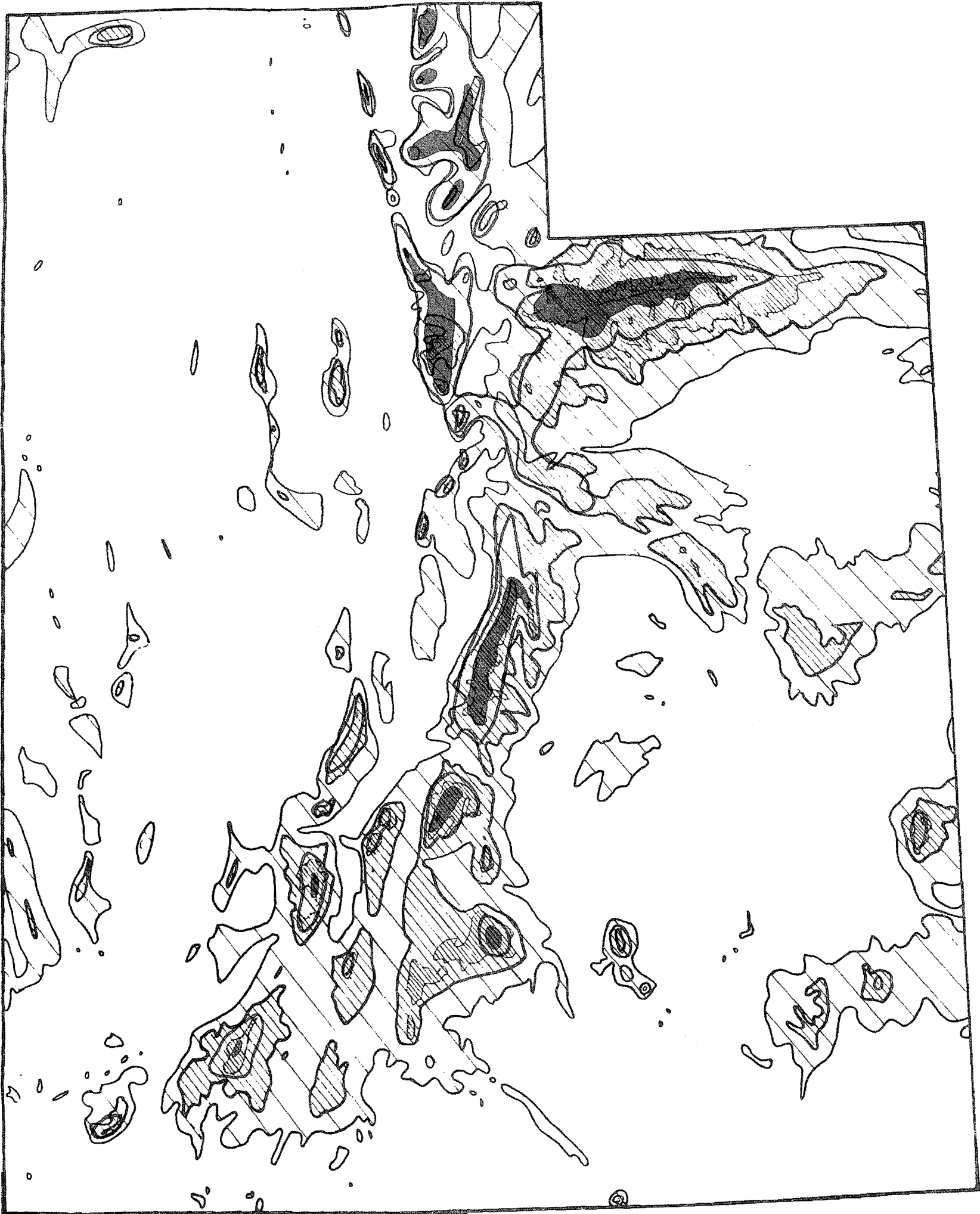


Figure 8. Median winter precipitation enhancement resulting from seeding one-third of total precipitation with an assumed rate of increase of 25 percent of that precipitation. Shaded areas 1.5 inches or more, contours, 1 inch.

winter precipitation augmentation potential actually is, it is highest where it is of greatest value.

2.3.2 Summer seeding potential. The summer seeding potential in Utah varies strongly according to the time of season. Therefore, the seeding potential is described herein on a monthly basis. The geographic distribution of precipitation increase for June, July, and August are shown in Figures 9, 10, and 11, respectively. In June seeding may be carried out, according to the previous calculations, for 59 percent of the precipitation; in July, 32 percent; and in August, 17 percent. For purposes of analysis, a 50 percent increase of that precipitation is assumed to occur from seeding. In each of the figures for summertime-precipitation increase, contours of three-tenths of an inch are shown. Lesser amounts of monthly precipitation are likely to be of little value.

In June, significant increase in precipitation, according to the assumed rate of increase, occurs over most of the elevated terrain in the north, and over the higher elevations in the south. During July, significant increases are expected only over the highest elevations in the south. And during August, no significant increases are expected anywhere in the State. It is noted that even though the precipitation is rather active in the south during late July and August, most of this precipitation is associated with thunderstorms, and therefore is not suitable for artificial seeding. Therefore, significant augmentation of summertime precipitation is most likely achieved in the north in early summer especially near or in mountainous terrain.

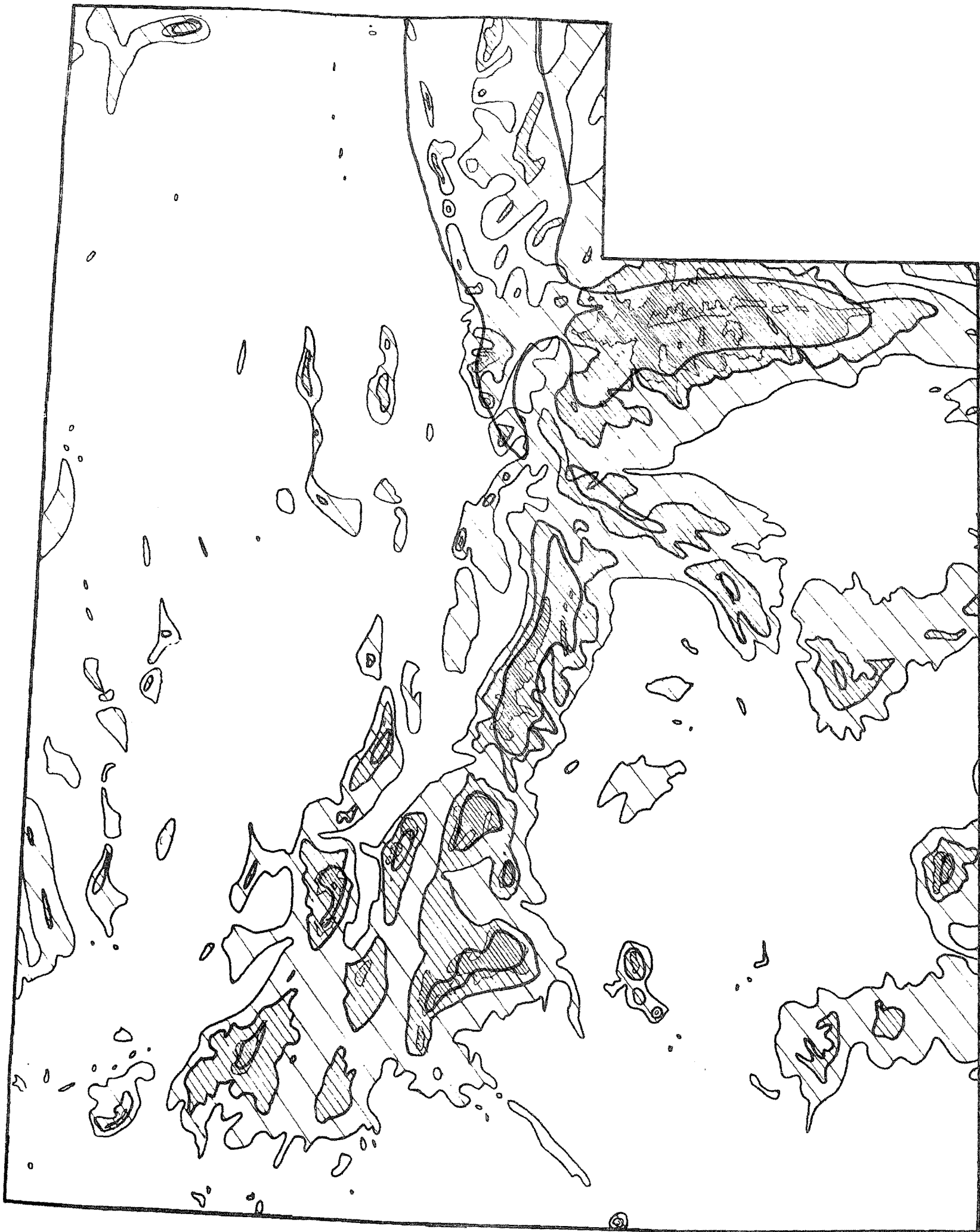


Figure 9. Median June precipitation enhancement resulting from seeding 59 percent of total precipitation with an assumed rate of increase of 50 percent of that precipitation. Contours, 0.3 inches.



Figure 10. Median July precipitation enhancement resulting from seeding 32 percent of total precipitation with an assumed rate of increase of 50 percent of that precipitation. Contours, 0.3 inches.

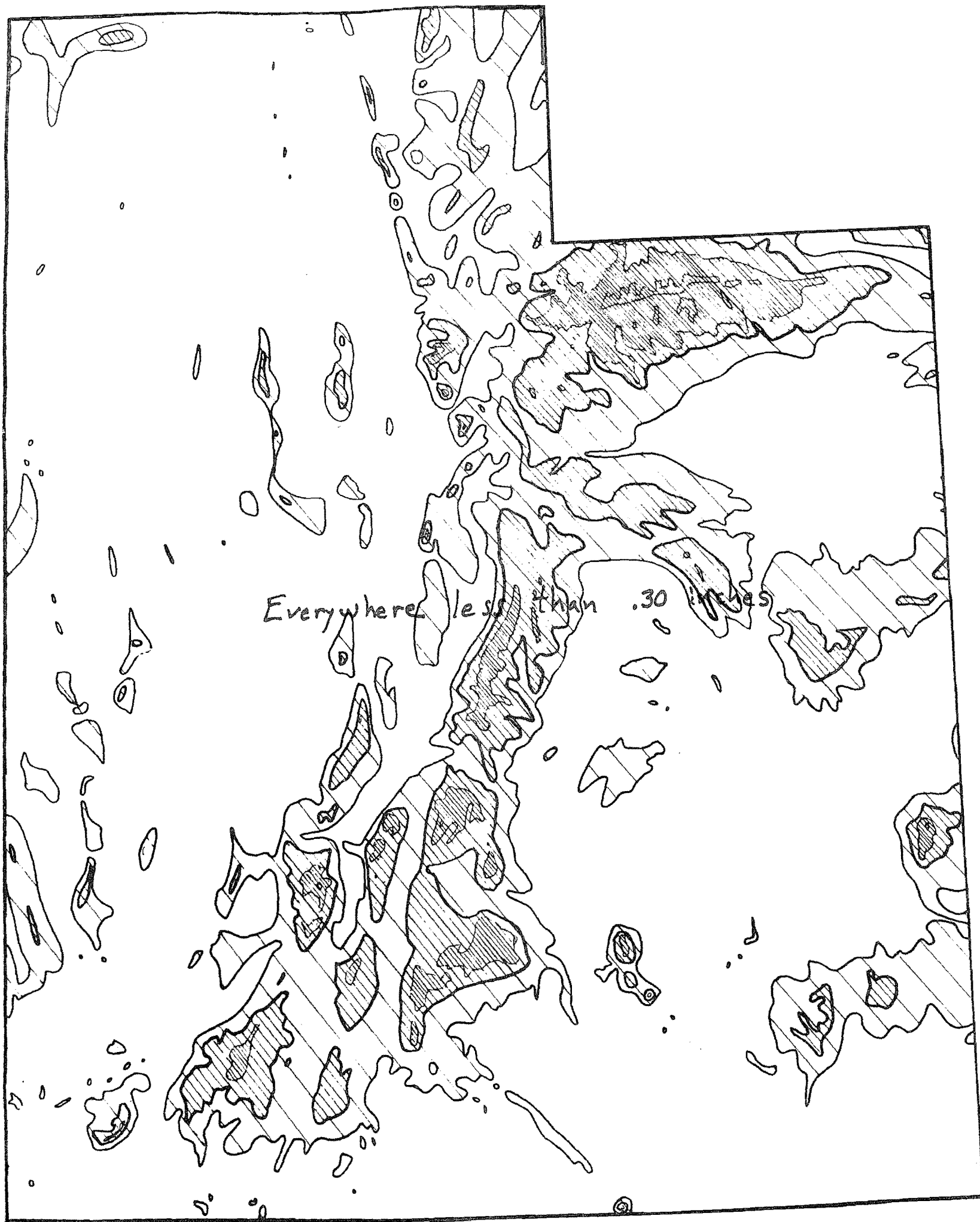


Figure 11. Median August precipitation enhancement resulting from seeding 17 percent of total precipitation with an assumed rate of increase of 50 percent of that precipitation. Contours, 0.3 inches.

2.3.3 Summary. To obtain an overall view of the augmentation potential, four values will be given in Table 1, along with the total precipitation for the general areas chosen and the fraction of seedable cases. The increases shown are, of course, consistent with the values given in Figures 8 through 11; they represent a summary.

Table 1. Precipitation augmentation potential

Season	Eleva- tion	Seedable Fraction	Total Precipitation (Inches)	Percent Increase	Increase (Inches)
Winter	High	.30	15	25	1.20
Winter	Low	.30	5	25	.45
Summer	High	.45	9	50	2.00
Summer	Low	.45	3	50	.67

The summer values given in the table are only approximate because there is a strong variation within the season. On a monthly basis the summer augmentation potential changes dramatically. The monthly summer variations in augmentation potential of precipitation are shown in Table 2.

It is evident that during the months of July and August only a very small increase in precipitation may be expected. Furthermore, the large year-to-year variations in precipitation during the summer months might preclude seeding during other months as well. For example, during June, 1974 there were probably no opportunities for seeding, primarily due to the lack of clouds of any type.

Table 2. Summer variation in precipitation augmentation potential

Month	Seedable Fraction	Total Precipitation (Inches)	50% Increase (Inches)
May	.70	1.77	.615
June	.59	1.27	.375
July	.32	1.02	.165
August	.17	1.43	.120
September	.45	1.43	.320
Summer Total Increase			1.595

To summarize, it is likely that during winter an opportunity exists to seed about a third of the cloud systems to yield a statewide increase in precipitation of about one-half inch to two inches assuming a 25 percent increase, and double these amounts for a 50 percent increase. Precipitation in higher elevations will be stored for spring runoff. During summer it is expected that worthwhile seeding can be accomplished only during May and perhaps early June. The yield would probably be around a few tenths of an inch over most of the State's arable land. Seeding potential is found rather dependable during winter in high elevations with a minimum of around 70 percent of the median potential. In summer the minimum drops to around 10 or 15 percent of the median.

3.0 UTAH STATE RULES, REGULATIONS AND PRO- CEDURES RELATING TO CLOUD SEEDING PROJECTS

3.1 Development of Rules, Regulations and Procedures

In collaboration with staff members of the State of Utah Division of Water Resources a set of rules, regulations and procedures relating to the Utah Cloud Seeding Act of 1973 was developed. These rules, etc., were written to insure that the requirements of the Cloud Seeding Act are properly carried out. A document which presents these rules, etc., has been published by the Division of Water Resources and therefore is not reproduced here.

4.0 RECOMMENDATIONS

4.1 Cloud Seeding Research

Because a great many uncertainties still exist in the field of cloud modification, a portion of any resources allocated for cloud seeding efforts should be devoted to research. The research could be carried out in any of several sub programs, such as (1) cloud modeling studies used for evaluation purposes, (2) statistical analyses of existing data, also for evaluation purposes, (3) experimental field programs designed to find out under what conditions cloud seeding is effective, (4) cloud seeding delivery technology to find out optimum methods of dispersing seeding material, and (5) review studies of other relevant cloud seeding projects.

These suggested studies need not be solely supported by the State, but rather joint support with Federal agencies such as the Bureau of Reclamation, the National Science Foundation, or the National Oceanographic and Atmospheric Administration is recommended.

4.2 Cloud Seeding Operations

There is evidently a growing interest in cloud seeding operations to increase precipitation in Utah. Based upon the upper limits of cloud seeding potentiality as described in section 2.0, it is recommended that if operational cloud seeding is conducted in Utah, the most reliable and greatest increases would be derived from seeding winter orographic clouds. Seeding should be done in such a way that the maximum effect is achieved in the highest elevations, where storage for spring runoff is greatest. Such an effort is no small task. For example, a rather different concentration of seeding material

would be required for varying distances from the target region. Whatever steps as would be required to utilize added winter precipitation ought to be made. Such steps might include construction of additional reservoirs in key locations.

For several reasons, widespread cloud seeding in the summertime is not recommended. One reason is that much of the precipitation in summer is derived from thunderstorms, wherein an already sufficient number of ice crystals exist. Furthermore, in Utah cloud bases in convective clouds are relatively high and much of the precipitation formed naturally or artificially would evaporate before reaching the ground. In those cases where the cloud bases are low precipitation is apt to be heavy though short-lived. In this case, cloud seeding has questionable benefits if not harmful. Another important reason is that summertime precipitation is highly variable and in some years may be sparse enough to cause drought conditions. In the absence of clouds, cloud seeding cannot be carried out. The best measure to offset drought conditions in an already semi-arid region is maximum use of snowmelt by effective storage and irrigation practices and by augmentation of the snowpack where possible.

4.3 Legal Measures

Based upon review of the Rules, Regulations and Procedures described in section 3.0 and the experience of one year's cloud seeding activity under those rules, two recommendations are made. The first is that the proposed Weather Modification Advisory Committee as described in Chapter II of the Rules be implemented. The second is that provisions be made for enforcement of the requirements stipulated in the Rules. Of particular concern are items 2 (c) and (d) of Chapter IX wherein provisions are made for monitoring promotional material and claims of seeding effectiveness.

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