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COMMENTS BY A HYDROLOGIC ENGINEER ON CLOUD SEEDING IN ARIZONA

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1. INTRODUCTION

In many arid and semiarid regions, rainfall is a major source of surface water supply. This is particularly true in much of the Southwest where runoff from small watersheds and river basins results primarily from thunderstorm rainfall (Osborn and Reynolds, 1963; Renard, 1970). In this paper some apparent results of cloud seeding in Arizona are discussed and some implications are pointed out to Southwest water users and others who are dependent to varying degrees on thunderstorm rainfall.

2. WATER YIELD IN ARIZONA

The importance of thunderstorm rainfall to water users varies from region to region in Arizona. In southeastern Arizona about 70 percent of the rainfall and almost all rangeland runoff results from intense, highly variable thunderstorms in July, August, and September. For example, there is a nonlinear correlation between thunderstorm rainfall (summer rainfall) and annual runoff based on 10 years of readily available data (USWB, 1955-1964; USGS, 1964 and 1970) for the San Pedro River drainage above the proposed Charleston Dam site (1220 square miles) (Table 1).

Table 1. Annual runoff and summer rainfall for San Pedro River above Charleston, 1955-1964.

Year	Summer rainfall	Measured runoff	Est. runoff (curve Fig. 1) +25% rainfall	-25% rainfall
	(inches)	(inches)	(inches)	(inches)
1955	13.2	1.34	2.3	0.7
1956	6.6	.30	.4	.1
1957	7.6	.35	.6	.2
1958	11.8	1.19	1.7	.5
1959	9.7	.65	1.1	.3
1960	6.9	.20	.5	.1
1961	8.3	.39	.8	.2
1962	6.3	.20	.4	.1
1963	8.8	.53	.9	.2
1964	11.5	.87	1.6	.4
Ave.	9.1			
Total		6.02	10.3	2.8

Because of this strong correlation, a curve can be drawn from which annual runoff can be predicted with reasonable accuracy from summer rainfall (Fig. 1). Average summer rainfall for the 10-year record was nine inches. Runoff for the average rainfall year would be about 0.55 inch, 36,000 ac-ft (Fig. 1). Arbitrarily assuming a 25% increase in summer rainfall due to seeding, and ignoring possible long-term changes in rainfall-runoff relationships or possible long term changes in the character of the thunderstorm rainfall, would increase runoff to about 0.95 inch, 65,000 ac-ft, or nearly twice as much runoff from an increase of 25% in summer rainfall. On the other hand, a similar decrease of 25% in summer rainfall would decrease runoff to about 0.25 inch, 16,000 ac-ft, which is less than one-half the runoff from an "average" year.

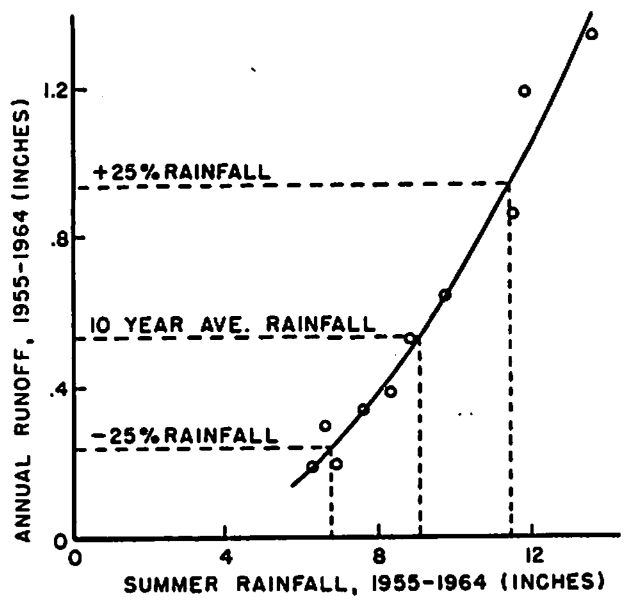


Figure 1. Annual runoff versus summer rainfall, San Pedro River above Charleston.

A rough, but revealing, estimate of probable effects of increasing or decreasing summer rainfall is to enter yearly rainfall amounts ± 25% into Figure 1, and to determine approximate annual discharges for each year (Table 1). Total measured runoff for the 10-year record was about 6 inches, 390,000 ac-ft. Increasing summer rainfall each year by 25% increased runoff to roughly 10.3 in., 670,000 ac-ft, an increase of about 80%. Decreasing rainfall each year by 25%, decreased runoff to 2.8 inches, 180,000 ac-ft, or less than 50% of average.

Although long-range effects of increasing or decreasing thunderstorm rainfall and the possibility of changing the character of thunderstorm rainfall by seeding suggest that this example is oversimplified, it does illustrate why so many persons in relatively arid regions are intrigued by the possibility of increasing thunderstorm rainfall, and at the same time rather nervous over the possibility of accidentally decreasing it.

The ratio of summer to winter rainfall in Arizona generally decreases both north and west of southeastern Arizona, and therefore the relative importance of thunderstorm rainfall is generally less in other parts of the state. In the mountainous regions of central and eastern Arizona, summer and winter rainfall are about equally important to local ranchers and residents. However, streamflow in the major rivers in the region results primarily from winter rain and snow and is stored in reservoirs for use in the most populated region in Arizona, the lower Salt River Valley. About one-half the state population is concentrated in the lower Salt River Valley, and this majority is naturally more interested in their principal source of water rather than in summer thunderstorm rainfall. The many individuals and groups involved with water development and use in this region are far more interested in the possibility of increasing winter precipitation in central and eastern Arizona and are justifiably jealous of their rights and responsibilities regarding possible man-made changes in winter precipitation. Since thunderstorm rainfall is considerably less important to the majority, questions of thunderstorm cloud seeding receive less attention.

Possible increases in available water from both winter and summer cloud seeding would appear to be equally important in northern and western Arizona, but such programs would directly affect relatively few persons, less than 10% of the state population, and therefore either experimental or operational cloud seeding programs receive relatively little support or opposition.

3. SANTA CATALINA EXPERIMENT

From 1957 through 1964 two successive thunderstorm cloud seeding experiments were carried out over the Santa Catalina Mountains in southern Arizona by the Institute of Atmospheric Physics at the University of Arizona. The experiments were under the direction of L. J. Battan and A. R. Kassander (1960). The first experiment was carried out during the summer months from 1957 through 1960, and the second in 1961, 1962, and 1964. Silver iodide was seeded upwind from the Santa Catalina Mountains for several hours beginning at about 12:30 pm at about 20,000 feet above MSL during the first experiment and about 12,000 feet (the cloud base) during the second experiment. Rainfall was estimated from a network of recording rain gages scattered over the Santa Catalinas.

Although there were some differences between the two experiments, the overall effects were about the same with about 30 percent less rainfall on seeded as opposed to not seeded experimental days. Battan (1966) concluded that, among other things, although there appeared to be, if anything, a decrease in rainfall because of seeding, "the statistical tests indicate that the observed results could have occurred readily by chance." Battan's final conclusion at that time was that "It appears safe to conclude that additional research is needed to resolve the conflicting views on the physics of convective precipitation and on the efficacy of various cloud seeding techniques."

Recent analyses by Neyman and Osborn (1971) of records from 26 recording rain gages on the USDA Walnut Gulch Experimental Watershed, 65 miles southeast of the Santa Catalinas, suggest negative effects of cloud seeding between 1957 and 1964 on experimental days when Walnut Gulch was "downwind" from the target. The separation of all experimental days into "upwind" and "downwind" categories based on two 180° subdivisions was crude, but deemed necessary because of the relatively small sample. In any case, the silver iodide nuclii could not have reached Walnut Gulch on "downwind" days, so possible modifications must have been indirect. Comparison of average rainfall amounts and distributions by 3-hour moving averages for an arbitrary period, 2:00 p.m. to 2:00 a.m., indicated that rainfall on seeded downwind days appeared to be suppressed and lacked the characteristic double peak recorded for non seeded days both at Walnut Gulch (Fig. 2) and in the Santa Catalinas (Fig. 3), and was about 40% of that on non seeded downwind days. Average hourly rainfall was also appreciably less on all seeded as opposed to all not seeded experimental days (Fig. 2).

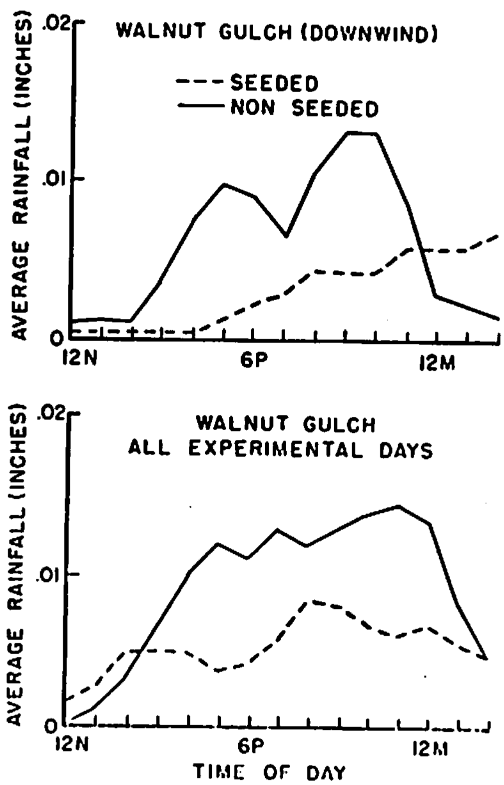


Figure 2. Average hourly rainfall on experimental days, 1957-1964.

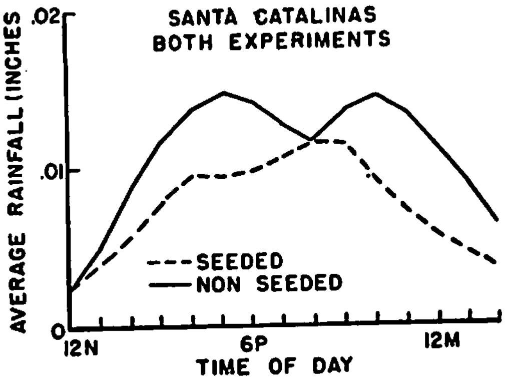


Figure 3. Average hourly rainfall on experimental days, 1957-1964.

Evaluation for experimental days by 24-hour periods, noon to noon, indicated about 40% less rainfall on all seeded as opposed to all non seeded days, which was statistically significant, and about 70% less rainfall on downwind seeded as opposed to downwind non seeded days, which was statistically highly significant (Neyman and Osborn, 1971).

More recent analyses indicate that differences between rainfall amounts on seeded and non seeded experimental days in the Santa Catalinas were greater during the second experiment (1961, 1962, and 1964) suggesting that changes in seeding methods between the two experiments may have been important (Fig. 4).

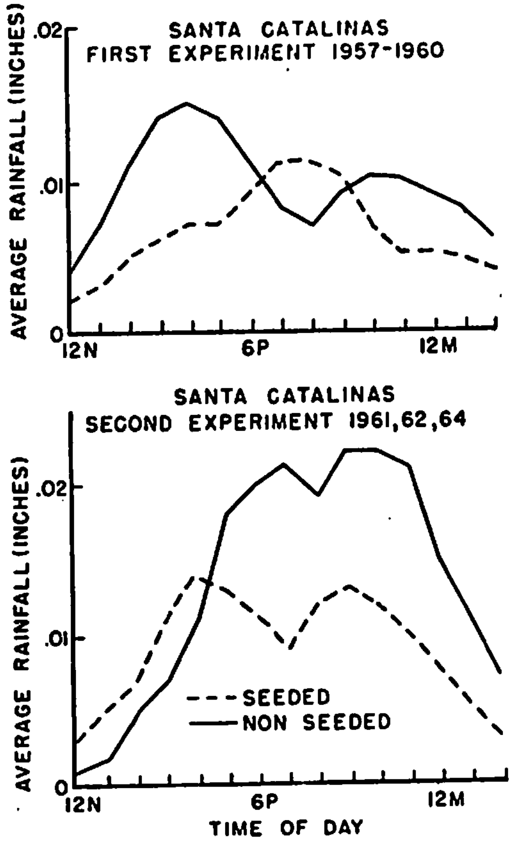


Figure 4. Average hourly rainfall on experimental days, Santa Catalina Experiments.

4. OTHER EXPERIMENTS

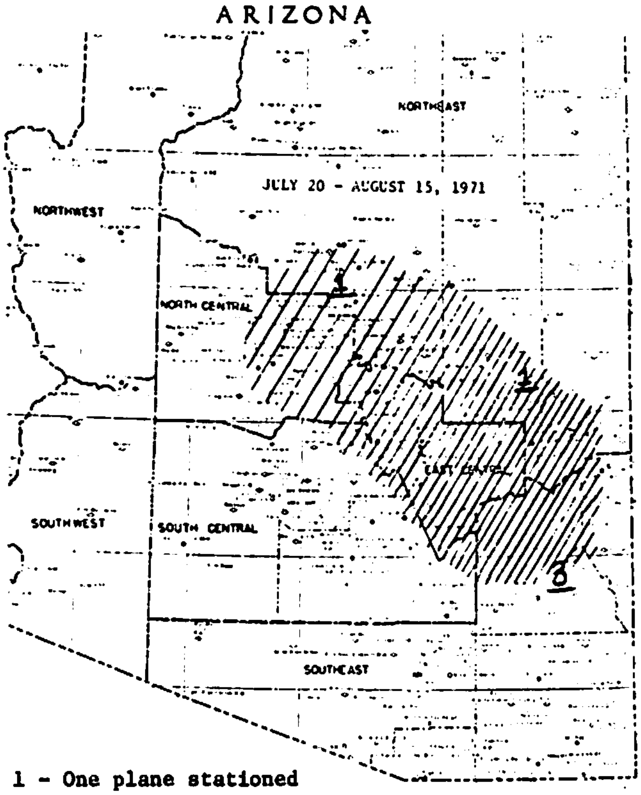
An experiment outside of Arizona that should be mentioned is one of the more comprehensive randomized, controlled convective cloud seeding experiments in this country—the well-known Whitetop Experiment in Missouri (Braham, 1966). Recent analyses of this experiment by Braham and Flueck (1970) and Flueck (1971) suggest negative effects of cloud seeding on and immediately downwind from the target. However, attempts to determine if there were more widespread effects from seeding were handicapped by a preponderance of heavy rains beginning early on not seeded days (Decker, Chang, and Krausse, 1971; Lovasich, et al., 1971). On the other hand, for example, two widely analyzed cloud seeding experiments in foreign countries—one in Switzerland and the other in Israel indicated positive effects from seeding, with the Swiss experiment suggesting particularly large and widespread effects (Gabriel, 1966; Neyman, Scott, and Wells, 1969; Wurtle, 1971).

5. 1971 ARIZONA CLOUD SEEDING

At the request of the State of Arizona, the U.S. Bureau of Reclamation supervised a 4-week program of cumulus cloud seeding to increase summer rainfall in eastern and central Arizona in 1971. Since reports from programs such as the Santa Catalina and Whitetop experiments suggesting undesired results from continuous seeding were known to the Bureau of Reclamation, seeding was on an individual cloud basis similar to the Florida experiments (Simpson and Woodley, 1971; Woodley, 1970) rather than over a duration of time. This fact, along with a scarcity of rain gages in the region, made it very difficult to evaluate the possible effects of seeding.

Planes were stationed at Flagstaff, Show Low, and Safford with the primary seeded region indicated in Figure 5. Reports released during the program by the Bureau of Reclamation were apparently calculations of expected rainfall based on a number of assumptions, including greater than normal rainfall. An increase of 400,000 ac-ft of water was reported over an area of roughly 20,000 square miles. This added up to 0.75 inch over the region, or roughly 15 percent of the estimated rainfall during the seeded period. An increase of 15 percent is well within any reasonable statistical confidence limits that could be placed on error estimates based on available rainfall data for the highly variable summer thunderstorms.

Rain gage records from 133 U.S. Weather Bureau stations in Arizona for the seeded period, July 20-August 15, were compared in an effort to evaluate the overall pattern of rainfall for the state. The locations of rain gages used in the analyses are indicated in Figure 6. Also, quads were drawn to emphasize the uneven concentration of rain gages within the network. The scarcity of rain gages in the central and northern parts of the state is particularly noticeable.



1 - One plane stationed at Flagstaff and one at Showlow.
3 - Three planes stationed at Safford.

Figure 5. Principal seeded region, Arizona, 1971.

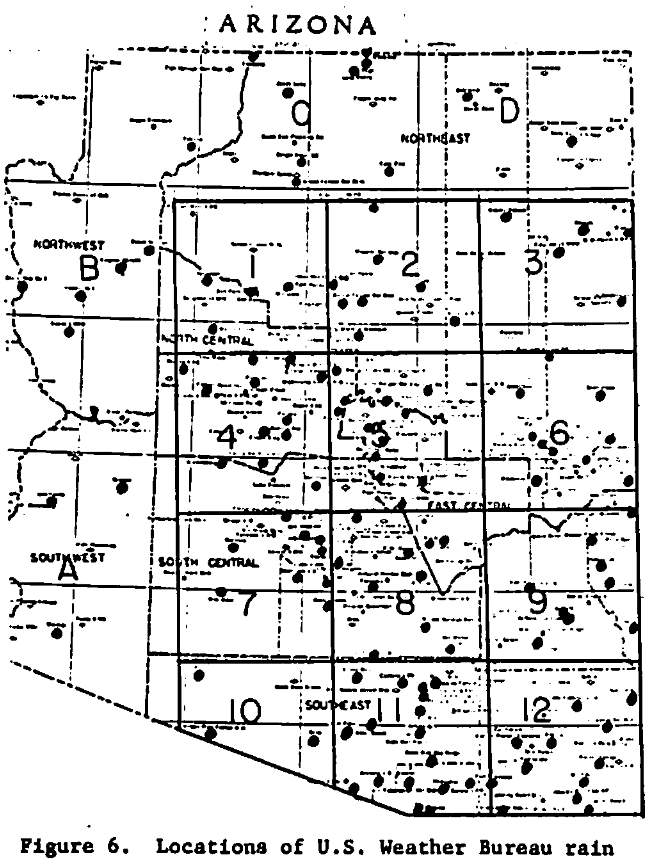


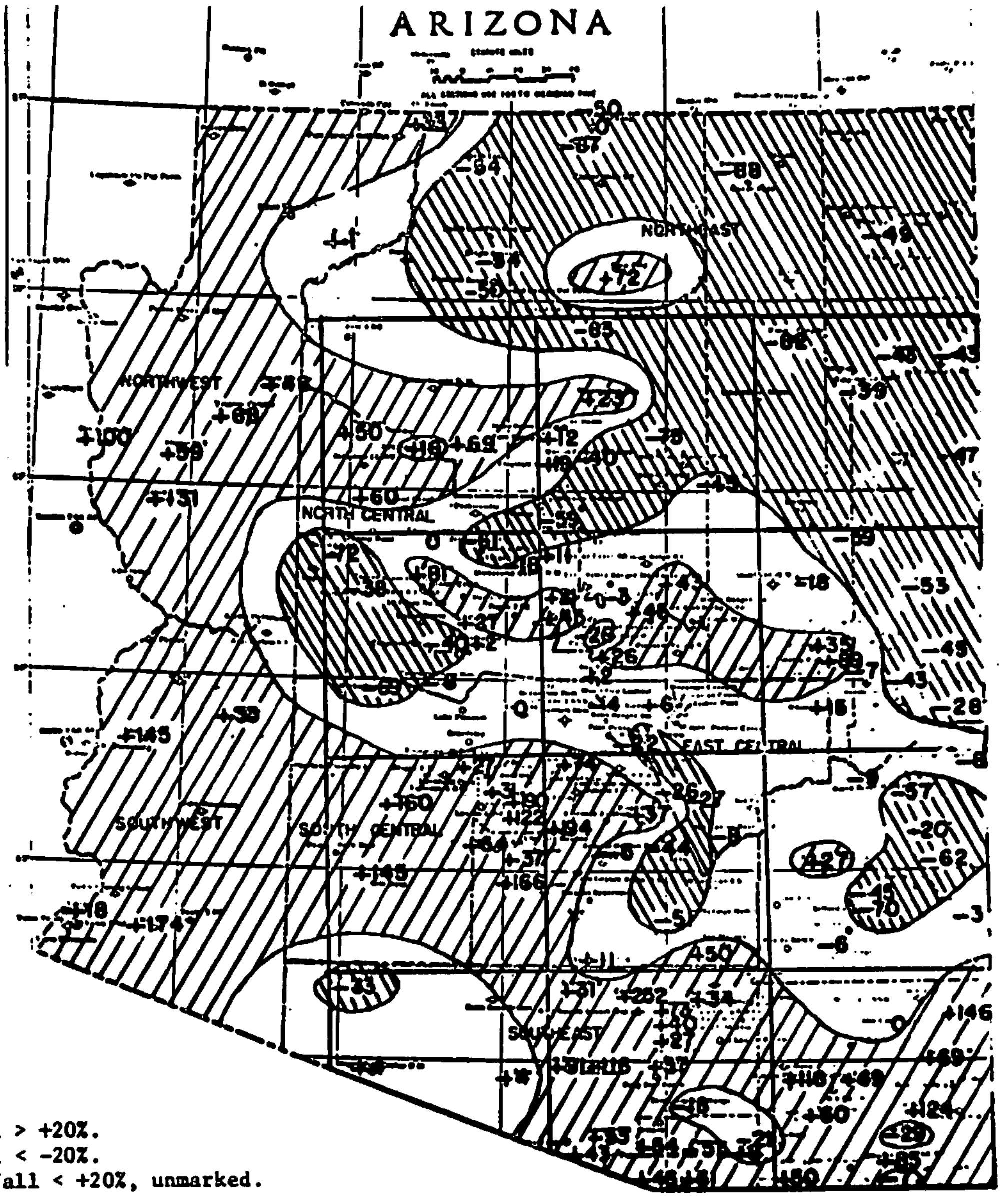
Figure 6. Locations of U.S. Weather Bureau rain gages used in analyzing cloud seeding, Arizona, 1971.

Station averages were determined for the seeded period using records from 1961 through 1970. Rainfall for 1971, for the seeded period, was compared with the 10-year average. Because of extreme rainfall variability, only stations with 20% more or less than the 10-year average were considered to be other than average for the year. A very rough estimate of the regions of Arizona that were above average, below average, and average is shown in Figure 7.

As would be expected, most U.S. Weather Bureau stations are concentrated in the more populated regions with only a few scattered gages within the seeded area and north and west of the seeded area. However, the records are sufficient to indicate that rainfall was generally far above normal in southern (upwind) and western parts of the state and far below normal north (downwind) and east of the seeded area. Records within the seeded area indicate scattered results, with overall rainfall within the seeded area apparently about average.

Whether any more rigorous analysis is possible is questionable because of inadequate data and control, but there is certainly no indication of an overall increase in the seeded area, and as stated, there was considerably more rainfall generally upwind from the seeded area and considerably less rainfall generally downwind from the seeded area. Although the overall pattern of rainfall during the seeded period could occur naturally, the similarities to observations in both the Santa Catalina and Whitetop experiments, plus postulations by Dennis and Schock (1971), concerning possible adverse effects of individual cloud seeding on the complex surrounding cumulus buildup, suggest that more comprehensive experimentation is needed before any further operational thunderstorm cloud seeding programs are carried out in Arizona or the Southwest. Actually, it may not be as important whether the program is called experimental or operational, as it is essential that proper randomization and controls are carried out so that the programs can be properly analyzed.

Several of the questions that an engineer might ask concerning increasing thunderstorm rainfall include: (a) if there is increased precipitation from silver iodide seeding in one region, does this imply a similar reduction in precipitation somewhere else; (b) if (a) is true, is there some pattern of silver iodide seeding that will increase rainfall in a desired location without decreasing it in another; (c) if there are local increases from individual cloud seeding within a region, are these increases more than offset by overall decreases in both the seeded region and for some distance from the seeded region; (d) if "a" or "c" is true, is there some material other than silver iodide that might increase thunderstorm rainfall in one locality or region without decreasing it in another; and, (e) will programs to suppress hail or lightning also decrease rainfall. None of these questions are new, but too many of the past and current cloud seeding programs appear not to have taken into account enough of them to be of practical value to engineers and others involved in decisions on water use and development.



///Rainfall > +20%.
\\\Rainfall < -20%.
-20% < Rainfall < +20%, unmarked.

Figure 7. Estimate of statewide Arizona rainfall, July 20-Aug. 15, 1971.

6. CONCLUSIONS

No absolute conclusions can be made from past experimental and operation cumulus cloud seeding programs in Arizona. Unfortunately, this appears to be the case elsewhere as well. From an engineering viewpoint, the two principal weaknesses appear to be inadequate measurement (or any measurement) of rainfall over a sufficiently large area and a lack of good solid experimental controls. There are a number of recent experiments that tease the reader's imagination, but no experiments of the necessary magnitude and design such as the earlier Santa Catalina and Whitetop experiments to answer the many questions that have been raised by these and other later experiments. Furthermore, anyone interested in water yield also is interested in the overall effects on precipitation of suppressing hail or lightning, and experimental programs in these areas also suffer from inadequate hydrologic data and control.

The questions raised concerning thunderstorm cloud seeding may seem somewhat academic in areas where thunderstorms produce only a small part of annual precipitation and therefore are relatively unimportant in water yield studies. The questions are critical, however, in such arid regions as southern Arizona where thunderstorm rainfall produces all or most of the annual water yield. There is real need to know the overall effect of individual cloud seeding both in time and space over a rather large area, probably greater than 1,000 square miles. The conclusions stated by Battan in 1966 are still valid; "it appears safe to conclude that additional research is needed to resolve the conflicting views on the physics of convective precipitation and on the efficacy of various cloud seeding techniques." The most important criterion for investigation is the absolute necessity to measure what actually happens to the rainfall.

7. ACKNOWLEDGEMENTS

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