Potential of Convective Cloud Seeding in the Southwest

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WATER users in the Southwest can be divided generally into those who use stored water (reservoir and/or groundwater) and those who depend upon rainfall for range forage and for livestock watering. These groups may or may not view weather modification similarly. The principal purposes for increasing precipitation in the Southwest are: (a) to increase the surface and subsurface water stored for municipal, industrial, mining, and irrigated agriculture users, and (b) to increase range forage for beef production. The former users are most interested in moving the most possible water from the watersheds into reservoirs and groundwater storage; the latter users are most interested in retaining as much water as possible on the land to improve range conditions.

Much of the land surface of Arizona and New Mexico is arid or semiarid, and in these lands, thunderstorms are the major runoff source. On rangelands in southeastern Arizona, for example, about 70 percent of the rainfall and almost all runoff results from intense thunderstorm rains in July, August, and early September (Dorroh, 1960; Osborn and Hickok, 1968). However, winter storms are significant sources of water supply for mountainous watersheds, such as parts of the Salt River System (the water supply for the greater Phoenix area).

CLOUD SEEDING IN THE SOUTHWEST

The most comprehensive randomized cloud seeding experiment in the southwest was carried out in the Santa Catalina Mountains during the summers of 1957-60, 1961, 1962, and 1964 (Battan, 1966). The purpose of the experiment was to determine the effects of silver iodide seeding on cumulus cloud rainfall. The result of the 7-yr experiment was a statistically non-significant overall decrease of about 30 percent in seeded rainfall (Battan and Kassander, 1967). A more recent analysis of possible wide-area effects from the Santa Catalina experiments indicated a statistically significant overall decrease in seeded rainfall of about 40 percent some 70 miles from the Santa Catalinas, and a highly significant decrease of 73 percent at the same location when it was "downwind" from the Santa Catalinas (Neyman and Osborn, 1971). To date, no evidence has been published to explain these results or to contradict their implications.

Individual cumulus clouds were seeded experimentally in northern Arizona in the late 1960s. A cloud model was used to estimate expected cloud buildup and rainfall at cloud base and compared to radar observations of seeded and unseeded clouds. No conclusions were reached on whether or not there were meaningful changes at ground level or over a wide area (Weinstein and McReady, 1968).

In 1971, an operational cloud seeding program was carried out to increase rainfall from cumulus clouds in central Arizona. Although there was no official effort to measure possible changes in rainfall, later admittedly crude analyses suggested that, if anything, the cloud seeding reduced rainfall in the region (Osborn, 1972).

Since 1971, there have been no cloud seeding efforts in Arizona and New Mexico, and there is a moratorium in effect on cloud seeding in New Mexico (Brook, 1973).

Other references that include analyses and comments on the Santa Catalina experiment are Battan (1969), Neyman et al. (1972), and Neyman, Scott, and Wells (1973). Two other references on cumulus cloud seeding in the Southwest are Weinstein (1972) and Grant (1973).

Some recent and comprehensive publications concerned with cumulus cloud seeding include (a) the report by the National Research Council, Committee on Atmospheric Sciences (1973), (b) "Cumulus Clouds and Their Modification" by Simpson and Dennis (1972), (c) the August 1975, issue of the Journal of Applied Meteorology, and (d) Chapter 7 on "Climate and Food" of the report by the National Research Council, Board on Agricultural and Renewable Resources (1976).

CUMULUS CLOUD MODELS

There are four basic areas of uncertainty in estimating runoff from cumulus cloud modification. The first is the natural variability of convective rainfall; the second is the uncertainty in parameter estimation in cumulus cloud models; the third is the variability of watershed characteristics; and the fourth is the uncertainty in parameter estimation of rainfall-runoff models.

A major problem in cumulus cloud modification is the wide natural fluctuations in all cumulus cloud parameters. Because of these fluctuations, simplified models have been developed to estimate effects of cloud modification. They are one dimensional, and, therefore, not meant to estimate areal rainfall. Berry (1976), in summarizing the results of the AMS special regional weaweather modification conference in Nov., 1975, stated that "no currently available model can predict the effects of seeding- - -on precipitation with sufficient accuracy to provide a reliable physical formulation for the experimental design. It is even possible that the physics is too complex to allow the construction of a model that can make these predictions to the required accuracy." The uncertainties inherrent in such models used to estimate rainfall are generally greater than the natural variability of rainfall.

OTHER AREAS OF UNCERTAINTY

Once rainfall has been estimated, another model

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TABLE 1. ANNUAL RUNOFF AND SUMMER RAINFALL FOR SAN PEDRO RIVER ABOVE CHARLESTON, 1955-1964 (AFTER OSBORN, 1971).

Year	Summer rainfall, mm	Measured runoff, mm	Est. runoff (from curve Fig. 1) +25% rainfall, mm	Est. runoff (from curve Fig. 1) −25% rainfall, mm
1955	335	34	58	18
1956	168	8	10	3
1957	193	9	15	5
1958	300	30	43	13
1959	246	17	28	8
1960	175	5	13	3
1961	211	10	20	5
1962	160	5	10	3
1963	224	13	23	5
1964	292	22	41	10
10 yr ave	231			
10 yr total		153	262	71

(10 mm = 0.395 in.)

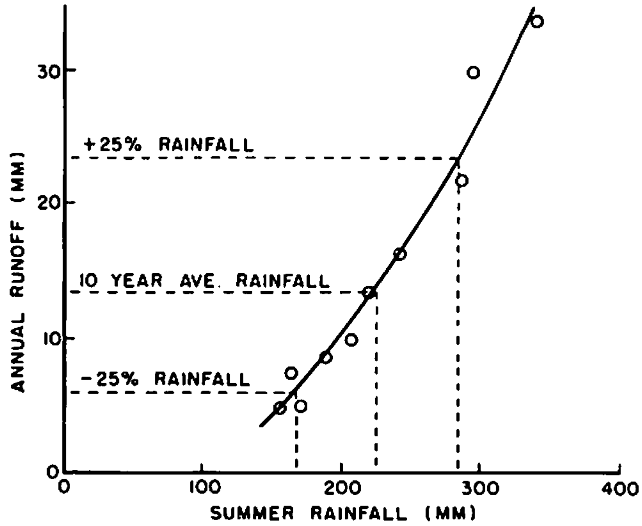

FIG. 1 Annual runoff vs. summer rainfall, San Pedro River above Charleston is 3160 km² (Osborn, 1971).

must be chosen to convert rainfall to runoff. The choice of this model will also affect the estimate of the output, and again, the parameters are uncertain. In addition, possible changes in rates and volume of runoff could be masked by varying watershed characteristics, making estimates of changes in runoff even more uncertain (Seely and Decoursey, 1975).

Attempts have been made to examine possible downwind and wide area effects of cloud seeding on an "after-the-fact" basis. These analyses have been inconclusive, although as stated earlier, generally indicating decreases in convective rainfall, without providing conclusive physical reasons for such effects. Questions of seeding effects outside the target area may never be answered, since instrumentation to accurately measure possible wide area changes in convective rainfall is extremely costly.

Finally, there are still controversies on the mechanisms involved in seeding cumulus clouds, the use of ground-based generators vs. aircraft-based generators and the extent, concentration, and longevity of seeding nuclei. Again, these problems are all magnified by the expense of measuring and analyzing cumulus cloud modification efforts.

WATER YIELD

In many Southwest river basins there is correlation between summer thunderstorm rainfall and annual runoff. For example, there is a strong correlation for the San Pedro River Basin in southeastern Arizona (Table 1 and Fig. 1). For a 10-yr period for the 3,160 km² drainage above Charleston, runoff was about 150 mm or $4.8 \times 10^8 m^3$. Assuming a 25 percent uniform increase in summer rainfall for each of the 10 yr, runoff would have increased by about 70 percent to 260 mm, or $8.3 \times 10^8 m^3$. Similarly, a decrease of 25 percent in summer rainfall would have reduced runoff by more than 50 percent, from about 150 to 70 mm.

Probable long-range effects of increasing rainfall with weather modification suggest this example is oversimplified. However, it does illustrate why so many researchers in relatively arid regions are intrigued by the possibility of increasing thunderstorm rainfall, and at the same time concerned about possible unplanned decreases.

The U.S. Department of Agriculture, Agricultural Research Service, Southwest Rangeland Watershed Research Center, Tucson, AZ, operates two densely gaged experimental watersheds: 150-km² Walnut Gulch Experimental Watershed in southeastern Arizona, and the 174-km² Alamogordo Creek Experimental Watershed in eastern New Mexico (for detailed descriptions of these experimental watersheds, see Renard, 1970). There are 95 and 65 recording rain gages, respectively, on the two watersheds. Records from the raingage network and the principal runoff-measuring structure on each watershed were used to estimate possible changes in runoff with varying modification efforts, again assuming that the modification efforts would accomplish their intended purposes.

Thunderstorm runoff in this region results from short-duration, intense rain of limited areal extent. Runoff-producing rainfall on a semi-arid rangeland watershed, like Walnut Gulch or Alamogordo Creek, generally results from thunderstorms that cover only a part of the watershed (Fig. 2). For this simplified analysis, the assumed result of cloud seeding, 7.6 mm, is added to the center depth, where no additional rainfall is assumed at the storm boundry.

Radar or mathematical models are used in most efforts to estimate the effects of convective cloud modification. In this analysis, storm center depth and run-

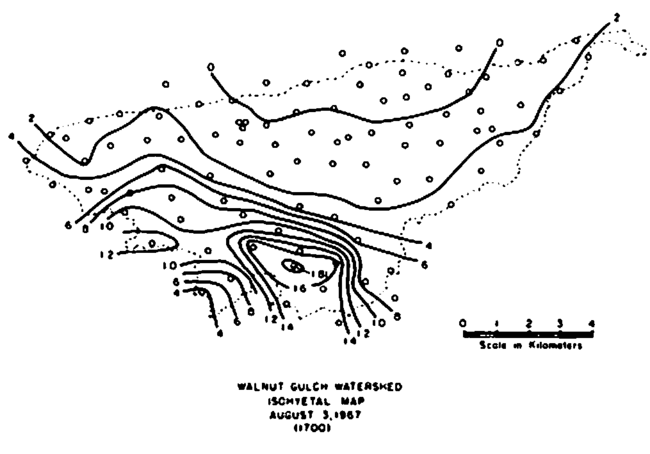

FIG. 2 Walnut Gulch Watershed Isohyetal map, August 3, 1967 (1700).

TABLE 2. ACTUAL VERSUS THEORETICAL SEEDED RAINFALL AND RUNOFF ON WALNUT GULCH, 1960-1971).

P, mm	Number of events	P ($10^7 m^3$)	ΔP* ($10^7 m^3$)	Q_p ($10^5 m^3$)	ΔQ* ($10^5 m^3$)	ΔQ/Q†
0 - 10.2	320	3.57	5.90	0.01	1.17	0.05
10.2 - 20.3	160	5.78	3.08	2.58	7.38	0.17
20.3 - 30.5	75	4.55	2.09	6.64	7.38	0.17
30.5 - 40.6	32	2.83	1.11	9.47	4.67	0.11
40.6 - 50.8‡	16	1.72	0.62	7.13	3.32	0.075

*Indicates seeded conditions
†Q = 4.43 x $10^6 m^3$ (total Walnut Gulch runoff, 1960-1971)
‡No estimates for storms with center depths greater than 51 mm were made.

(1000 m^3 = 0.813 ac-ft)

off (which are highly correlated) were determined for all storms on Walnut Gulch and Alamogordo for 12 yr (1960 to 1971). The frequency curves were then smoothed. Storms were grouped in 2.54 mm increments. Twelve years' data were used so the less frequent exceptional storms were included.

Total runoff for 12 yr was about 4.31 x $10^6 m^3$ and 1.43 x $10^7 m^3$ for Walnut Gulch and Alamogordo Creek, respectively. Rainfall increments were combined to estimate the theoretical rainfall and runoff increases from an assumed increase of 7.6 mm for each event. The combined increments were 0 to 10.2, 10.2 to 20.3, 20.3 to 30.5, and 30.5 to 40.6 mm (Tables 2 and 3). There were about 320 and 240 events less than 10.2 mm center depth during the 12 yr of record on Walnut Gulch and Alamogordo Creek, respectively. Total rainfall for these events was about 3.57 x $10^7 m^3$ for both watersheds (an average event on Alamogordo Creek would be similar to that on Walnut Gulch, but cover a larger area). For the assumed 7.6 mm increase in center depth for each event, rainfall volume was increased by about 5.90 x $10^7 m^3$ and 7.63 x $10^7 m^3$ on Walnut Gulch and Alamogordo Creek, respectively. This increase in rainfall should afford significant forage production increase and livestock water in small stock ponds. However, the predicted increase in runoff is almost negligible on both watersheds, because runoff production is normally small for such small events, and any runoff produced is abstracted within the ephemeral sand channels before reaching the watershed outlet. The increase in runoff for 12 yr, based on successful seeding of these smaller events, would be about 2.5 percent for Walnut Gulch and about 0.5 percent for Alamogordo Creek.

For the 160 and 120 storms on Walnut Gulch and Alamogordo Creek respectively, for the next combined increment (10.2 to 20.3 mm) the theoretical increase in rainfall from seeding would be about 50 percent and 100 percent, respectively, which would result in an estimated percent increase of 17 and 4, respectively, in total runoff. For the 75 and 70 storms of between 20.3 and 30.5 mm on Walnut Gulch and Alamogordo Creek runoff would be increased by about 17 and 13 respectively. For 32 storms of between 30.5 and 40.6 mm, seeding would increase runoff on Walnut Gulch Alamogordo Creek by about 11 and 17 percent, respectively. Similarly, the runoff increases for the 40.6-50.8 increment would be 7.5 and 12 percent for Walnut gulch and Alamogordo Creek, respectively. Theoretically, adding 7.6 mm to the 600 events on Walnut Gulch and the 500 events on Alamogordo Creek with center depth of less than 55 mm would increase the runoff by about 50 percent on each watershed.

The differences in storm distribution and areal extent for Walnut Gulch and Alamogordo Creek are emphasized when the ratios of estimated seeded rainfall to estimated seeded runoff are compared (Fig. 3). The smaller events on Alamogordo Creek are generally less-intense and cover much-larger areas. Therefore, theoretical increases in rainfall from seeding would produce less runoff on Alamogordo Creek. However, the larger events also are generally larger in areal extent on Alamogordo Creek than on Walnut Gulch, and more runoff is recorded. No conclusions should be drawn from the relative slopes for the two curves, since the sample is relatively small (600 and 500 storms), and there are uncertainties in the estimate, as well as possible errors in the actual measurements.

Increases in summer rainfall in the Southwest are normally most desired early in the thunderstorm season (Perry, 1976), when the storms are more likely to be small or when the cumulus-cloud buildup dissipates, before appreciable rainfall occurs. Successful seeding of these events would certainly improve range conditions, but would have little effect on runoff from larger

TABLE 3. ACTUAL VERSUS THEORETICAL SEEDED RAINFALL AND RUNOFF ON ALAMOGORDO CREEK, 1960-1971).

P, mm	Number of events	P ($10^7 m^3$)	ΔP* ($10^7 m^3$)	Q_p ($10^5 m^3$)	ΔQ* ($10^5 m^3$)	ΔQ/Q†
0 - 10.2	240	3.58	7.63	0.06	0.74	0.006
10.2 - 20.3	120	6.15	6.40	0.80	5.23	0.04
20.3 - 30.5	70	5.78	5.41	5.23	18.45	0.13
30.5 - 40.6	40	5.29	4.18	17.22	24.60	0.17
40.6 - 50.8‡	22	3.44	2.21	23.37	17.22	0.12

*Indicates seeded rainfall and runoff
†Q = 1.43 x $10^7 m^3$ (total Alamogordo Creek runoff, 1960-1971)
‡No estimates for storms with center depths greater than 51 mm were made.

(1000 m^3 = 0.813 ac-ft)

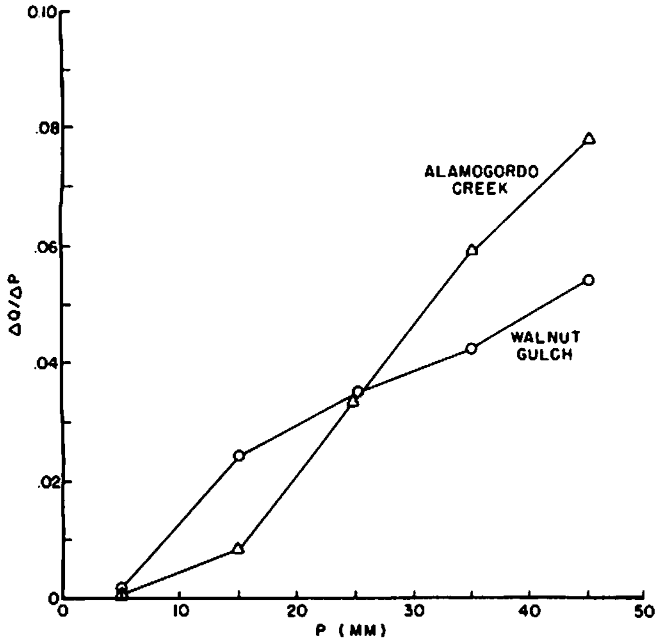

FIG. 3 Ratio of increase in runoff to increase in precipitation vs. increase in precipitation for Walnut Gulch and Alamagordo Creek.

watersheds. The objective of several operational cloud-seeding efforts in the West has been to increase rainfall from the small or trace storms.

For downstream water users, the greatest value from cloud seeding would be to increase rainfall from the moderate-sized storms (Tables 2 and 3). However, accidentally decreasing rainfall from these events would be disasterous. At present, the state-of-the-art is inadequate to guarantee increase from seeding of moderate-to-larger thunderstorms.

Efforts to increase rainfall from the major storms would be less advantageous because they are infrequent and difficult to forecast beforehand, and because relatively small increases in rainfall could cause large increases in runoff volumes and peak discharges and result in large detrimental increases in erosion and sediment transport.

In 12 yr of record, there were two storms that produced runoff equal to the average annual runoff from Walnut Gulch, and four events on Alamogordo Creek that produced about half of the 12-yr runoff. These major events present serious problems in analysis of effects of weather modification on runoff. If such an event should occur on a "seeded" day, seeding could look very good; if the event occurred on a nonseeded day, the ratio of seeded to nonseeded runoff could look very bad. Thus, these infrequent events can greatly bias any effort at analyzing effects of weather modification on runoff, particularly when most experiments or programs are designed to run for only a few years.

CONCLUSIONS

The potential for seeding convective clouds in the Southwest is limited by uncertainties in measuring or estimating rainfall and runoff. Thunderstorms are widely scattered and highly variable in intensity, duration, and areal extent. Cloud models developed to estimate possible seeding changes in clouds are, by necessity, simplified, and the uncertainty within them is generally greater than the predicted change in rainfall. Also, both the choice and inaccuracies in rainfall-runoff models increase the uncertainty of the estimates. Seeding opportunities are limited, and the storm systems with greatest potential for meaningful increases may not be identifiable in advance. Finally, cloud seeding efforts to date, although not conclusive, have suggested significant decreases in convective rainfall, both in the target areas and downwind, and these results have not been explained or contradicted by more recent developments in weather modification.

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