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# PRECIPITATION GAUGE SITING FOR EVALUATION OF AN OROGRAPHIC CLOUD SEEDING DEMONSTRATION PROJECT IN THE CENTRAL ROCKY MOUNTAINS

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## ABSTRACT

A winter orographic cloud seeding demonstration program is being planned for one or more of the high-water yield subbasins within the Upper Colorado River Basin. The primary response variable to be analyzed is the mean areal precipitation for 24-hour or shorter time intervals. The precipitation gauge network design includes the following specifications: gauge resolution of 0.025 cm; gauges installed at well protected sites such as small clearings in forests; gauges placed in a quasi-uniform areal distribution; the full range of elevations and aspects sampled; most gauges installed above 2900 m.

## 1. INTRODUCTION

A winter cloud seeding demonstration program is being planned by the Bureau of Reclamation for certain high-elevation regions of the UCRB (Upper Colorado River Basin). The primary evaluation will concentrate on quantifying changes in precipitation throughout the target areas. However, key links in the chain of physical events will also be monitored to establish reasonable confidence that it is cloud seeding which is responsible for changes in snowfall. Because of the importance of adequate precipitation measurements, significant emphasis is being placed on designing a precipitation gauge network which will enhance the potential to detect the expected changes. This paper describes the important water-producing regions within the Basin, the primary evaluation factors which have been considered and the specifications which have evolved thus far concerning the design of a precipitation gauge network.

## 2. PRIMARY RUNOFF-PRODUCING AREAS

Most of the precipitation which enters streams and reservoirs as runoff is collected from areas primarily located above 2800 m*, and very little runoff comes from elevations below 2300 m (Crow, 1967). The entire Colorado River watershed above Lee Ferry, the dividing point between the Upper Basin and Lower Basin, contains 283 600 km$^2$ but has an average annual runoff of only 5.8 cm. Approximately 77 percent of the total annual Upper Basin runoff comes from about 12 percent of the Basin area (33 670 km$^2$) which yields 25.5 cm or more in runoff. An additional 10 percent of the Upper Basin runoff is produced from about 9 percent of the Basin area (24 600 km$^2$) which yields 2.5 to 25.5 cm in runoff.

The 33 670 km$^2$ which produce an average of about 33 cm of runoff are the dominant sources of water supply in the UCRB. This area, indicated in Figure 1, is subdivided into eight major runoff regions that are generally above the 2900-m elevation. Areas furnishing 2.5 to 25.5 cm in annual runoff (mean of 7.6 cm) are also show in Fig. 1.

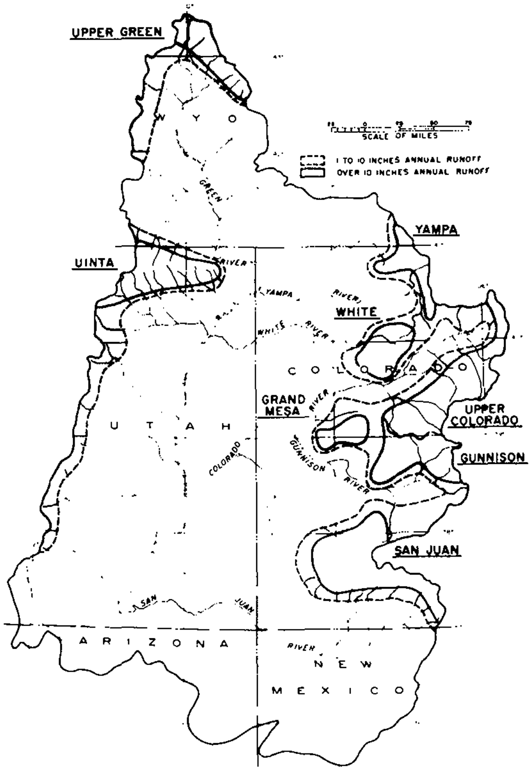

*Fig. 1. - Primary runoff-producing areas of the Upper Colorado River Basin.*

Klazura (1983) provides a comprehensive description of the winter precipitation characteristics within the Basin, particularly in the primary runoff-producing areas.

## 3. BASIC DESIGN OF CLOUD SEEDING PROGRAM

A randomized, target-control design is expected to be employed in the winter

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*Elevations are above mean sea level.

orographic cloud seeding demonstration program. The control areas will be in close proximity for higher correlation, and upwind of selected target areas. The experimental test unit is expected to be 24 hours or shorter.

The primary response variable to be analyzed is the mean areal precipitation (MAP). Several levels of analyses pertaining to MAP will be done. MAP computations will be made for the control area, the entire target area, and subareas within the target.

## 4. PRECIPITATION GAUGE SITING

### 4.1 Measurement Resolution

A high frequency of small precipitation events occurs in the Basin. More than 35 percent of the days with precipitation produce a water-equivalent accumulation of less than 0.25 cm† (Hartzell and Crow, 1976). The magnitude of the change in precipitation yield due to cloud seeding on a seasonal basis is expected to be on the order of 10 to 15 percent (although the change may be much larger for certain individual events). Because of the high frequency of small precipitation events, a resolution of 0.025 cm is desired.

### 4.2 Elevation Interval

As indicated previously, most of the precipitation which is converted to runoff is collected from areas primarily above 2800 m. Therefore, most gauge sites will be above this elevation. The tree line in the Basin generally is between 3400 and 3600 m. As discussed in section 4.3, uncertainty in the accuracy of snow catch increases significantly in unprotected, wind-swept regions. Therefore, gauges should be located in clearings in the forest which limits their use to below about 3600 m. Some portions of the higher-water yield areas of the UCRB have little tree cover, and adequate precipitation monitoring may be impractical in these high altitude zones.

### 4.3 Exposure

Exposure characteristics must be carefully considered in identifying suitable sites for the placement of precipitation gauges. Exposure is one of the most important factors in determining the rate and accumulation of winter precipitation (Klazura, 1983). The primary exposure characteristics are as follows:

A. Microscale site exposure . - The degree of protection (or nonprotection) afforded by nearby objects (primarily trees).

B. Mesoscale site exposure. - Exposure of measurement sites to the various moist flow sources determined by the larger scale topographic features including surrounding barriers.

C. Slope. - Rate of change of elevation in immediate area of the individual sensors.

D. Aspect. - Specification of the primary direction (azimuth) in which the site is open to moist flow.

E. Mean winter-season precipitation. - Values of seasonal precipitation and precipitation gradient along slope vector.

Item A relates to the accuracy with which snowfall can be measured. Items B, C, and D, along with elevation are controlling factors which determine the quantity and rate of precipitation accumulation. Item E provides predictive information regarding expected precipitation quantities and regions of greatest variation.

These classifications should be defined in quantitative terms. Each gauge location should be described by a set of classification values. This will allow a much more meaningful analysis of precipitation data. Quantitative characterization of gauge sites will lead to improved site selection and larger interstation correlation between the target and control.

The degree of protection for a given site (Item A) is a particularly important factor. Data from poorly-protected gauges can introduce excessive noise into the computations of MAP (Goodison, 1978), and possibly obscure the seeding signal. Israelson (1967) states that improper siting of snow gauges is the major cause of measurement error. The effect of wind speed on snow collection is significantly more critical than on rain collection. Even with a shielded gauge, wind effects still produce an appreciable deficiency in gauge catch for snow (Larson and Peck, 1974). With a 5 $ms^{-1}$ wind, the gauge catch deficiency is about 13 percent for rain, 30 percent for snow with a shielded gauge, and 50 percent for snow with an unshielded gauge (Larson and Peck, 1974). Even an elaborate shielding system such as developed by the University of Wyoming (Rechard and Wei, 1980) was insufficient to permit accurate snowfall measurements in exposed locations (Sturges, 1984).

Significant effort should be exerted to find well-protected sites. Based on limited comparisons of snowcourse and precipitation gauge observations, Brown and Peck (1962) suggested that a well-protected site would be a forest opening, completely surrounded by trees which subtend angles of 20° to 30° from gauge orifice with none greater than 45°. Further studies to determine the optimum clearing size would be useful.

### 4.4 Gauge Density

The proper gauge density for the demonstration program is a difficult specification to determine. In addition to other factors, it is dependent on the integration time (i.e., hourly, daily, monthly, seasonal, etc.) and magnitude of the precipitation accumulations (Huff, 1970), the type of precipitation events being sampled (Huff, 1971), and the spatial definition required (Eddy, 1976). The costs

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†Precipitation amounts are equivalent water depth.

and logistical aspects create additional restraints which cannot be ignored. The objective is to determine the minimum density which will allow the expected precipitation changes to be detected and quantified to an acceptable level of confidence.

Molnau, *et al.* (1980) analyzed data from a dense network of gauges located in a mountain watershed in Idaho to determine the optimum gauge density for estimating mean annual precipitation. When the gauge density decreased below one gauge per 12 $km^2$, the confidence interval widened rapidly. This suggests that if an accurate estimate of MAP is required to detect small changes in precipitation due to seeding, a density of about one gauge per 12 $km^2$ may be required without the use of covariates. Since the integration time is planned to be about one day rather than the entire year, and the terrain of the UCRB is much steeper and more complex, the gauge density requirement would probably be greater.

Although not definitive in itself, it is useful to consider what gauge densities were considered adequate in past winter orographic cloud seeding experiments with precipitation changes that were statistically significant at the 5 percent significance level or better. Mooney and Lunn (1969) reported on a five-season study which took place near Mt. Lassen, California. Seeding of a certain category of cloud systems was found to increase precipitation by an average of 37 percent throughout the target area, with a 57 percent peak occurring between 8 and 18 km from the leading edge of the target area. The gauge density used was one per 16 $km^2$.

Hicks and Lunsford (1970) performed detailed correlations on actual precipitation data used in a winter orographic weather modification experiment in the Jemez Mountains in New Mexico, and recommended that a minimum density of one gauge per 65 $km^2$ should be used. Solak, *et al.* (1984) recommended a density of one gauge per 57 $km^2$ in support of a winter orographic cloud seeding experiment in the Sierra Nevada Mountains of California.

Analyses of data from two winter orographic cloud seeding programs were performed in order to arrive at a minimum gauge density which could be used in the UCRB demonstration program. The first program scrutinized further was the Bridger Range Experiment conducted near Bozeman, Montana. A re-analysis of this experiment, employing control precipitation, yielded strong statistical evidence that seeding increased the seasonal precipitation by about 15 percent (Super and Heimbach, 1983). Seeding-associated increases of about 50 percent were found for certain categories of cloud cases. The gauge density used was one per 24 $km^2$.

One-tailed Wilcoxon probabilities (P-values) and double ratios were calculated for individual gauges, and for subsets of all combinations of two, three and four gauge groups that might realistically be chosen to represent the entire 310 $km^2$ target area. This was done for two ridge temperature partitions reported by Super and Heimbach (1983); that is, for experimental days colder than -9 °C and -13 °C, respectively. As the results were similar only the former case, with 100 experimental days is given in Table 1.

Assuming the results with the network of 13 gauges are realistic, the likelihood of P-values degrading increases as the number of gauges decreases. If the 12 combinations yield reasonably representative results of the distribution of P-values, then results suggest that using two (three) gauges allows a reasonable chance of detecting a seeding effect since all but one combination yielded P-values of .04 (.03) or less. Use of four gauges suggests a very good possibility of detecting the assumed effect.

Using only one gauge runs a serious risk of showing no significant effect as 5 of the 13 runs yielded P-values larger than .05. Four of these ranged from .07 to .09, with the highest value .35. Additionally, Table 1 shows that double ratios are reasonably stable if two or more gauges are used, with the maximum range from 1.44 to 1.74 (44 to 74 percent increases).

Interestingly, further analyses indicated a single gauge which had a P-value of .35 was responsible for most of the degradation. It was a member of each combination of gauges that yielded the highest group P-value. It also produced the lowest double ratio (1.21). It is not obvious why that gauge so affected the results. Its location in the bottom of a steep-walled canyon may have been a factor, possibly due to its relatively low elevation, or to local airflow channeling. Yet, at the time of gauge installation, that location was not judged inferior enough to select another site. It is likely that similar "errors in

Table 1. - P-values and double ratios for gauge combinations from Bridger Range Experiment

| No. of gauges | No. of combinations attempted | P-values |  |  | Double ratios |  |  |
|---|---|---|---|---|---|---|---|
|  |  | Highest | Mean | Lowest | Highest | Mean | Lowest |
| 13 | 1 | -- | .008 | -- | -- | 1.56 | -- |
| 4 | 7 | .03 | .013 | .006 | 1.71 | 1.59 | 1.49 |
| 3 | 12 | .07 | .022 | .004 | 1.74 | 1.58 | 1.45 |
| 2 | 12 | .07 | .023 | .008 | 1.66 | 1.56 | 1.44 |
| 1 | 13 | .35 | .065 | .001 | 1.98 | 1.49 | 1.21 |

judgement," if that was indeed the case, take place in the selection of some gauge sites in any experiment. Even with adequate catchment some sites will yield data with noticeably higher variance than others due in part to complex interactions between storm characteristics and larger-scale terrain factors.

Assuming that the gauges within each gauge group were well distributed throughout the area of interest, a realistic MAP value could be estimated. Utilizing these assumptions the Bridger Range experimental data suggest that three to four gauges over the 310 km$^2$ target area (one gauge per 78 to 103 km$^2$) would be adequate with the target-control design and control precipitation as the single covariate. However, many of the mountain ranges within the UCRB are more rugged and will produce more nonuniform precipitation patterns than occur in the Bridger Range. That area also offered widespread forest cover with natural clearings suitable for protecting gauges from wind-induced errors. Many higher mountain ranges in the UCRB have large areas above timberline. In such terrain, the only suitable precipitation gauge sites may be on the lower slopes and valleys where forests exist. This factor may seriously compromise attempts to achieve proper gauge spacing. The net result of these terrain-feature differences may be a higher gauge density requirement in the UCRB.

Medina and Mielke (1985) have looked at the gauge density issue with use of a data set collected as part of the Colorado River Basin Pilot Project (Hartzell and Crow, 1976; Elliott *et al.*, 1978), a five-winter, randomized cloud seeding experiment conducted over the San Juan Mountains of southwestern Colorado. Precipitation data were available for portions of the five winters (1970-75) for nearly 100 gauge locations, although areal coverage was not as uniform as desirable due to logistic retraints. Medina and Mielke employed the use of rerandomization and multiple-response permutation procedures to study the roles and interactions of project duration, probability of detection of known differences and gauge density. By the use of historical data with the rerandomization approach, essentially many experiments could be simulated by inserting known increases in the precipitation values. Such procedures allow results to reflect a more realistic impact of the variability of precipitation for a given area.

Results of their analyses indicate that approximately one gauge per 10 km$^2$ would be required for a 95 percent probability of detection of a 30 percent increase in precipitation in 200 experimental cases with one-half treated. A gauge density of one per 85 km$^2$ is required for a 90 percent probability of detection. By increasing the number of experimental cases to 240 (one-half treated) and inserting a 30 percent increase, the required gauge density is approximately one per 80 km$^2$ for a 95 percent probability of detection. The Colorado River Basin Pilot Project achieved 147 experimental cases (71 treated) during the 5-winter project period or approximately 30 cases per winter. At this rate, the 240-case requirement would lead to an 8-winter project period.

In considering all of the preceding body of information and evidence, it appears that a gauge density of one per 50 to 80 km$^2$ would be a reasonable estimate of the minimum required density. This assumes that a target-control design would be used with control precipitation as the primary covariate.

### 4.5 Gauge Distribution Pattern

If no knowledge were available regarding the precipitation distribution of the region, the simple choice for gauge network pattern would be a uniformly spaced grid. The mean winter isohyetal map represents a body of knowledge which provides fairly accurate information on where the precipitation peaks and gradients occur on a seasonal basis. It appears reasonable to distribute the gauges in clusters centered on the expected precipitation peaks. However, Kagan and Polishchuk (1971) and Stol (1972) indicate that this will not provide a better estimate of MAP. Chemerenko (1972) provides a very strong, systematic argument for placing gauges in a uniform distribution. He shows how an increase in the number of gauges does not necessarily decrease the error. In fact, he showed how the MAP error increases when certain regions are oversampled.

Ideally gauges should be located where the daily MAP estimate variance is minimized. However, adequate daily precipitation data for variance estimation is generally unavailable for complex mountainous terrain. Consequently, available seasonal data may be employed to help in gauge siting. Corbett (1967) indicates that a uniform distribution of gauges is best for determining areal amount and variability of precipitation for areas of flat terrain, but that in mountainous areas the elevation and aspect as well as area must be fully sampled to derive accurate estimates of precipitation over a watershed (Wilm, *et al.*, 1939; Kawabata, 1960). Hartzell and Crow (1976) and Hanson (1982) stress the importance of placing gauges on different facing slopes within a given barrier in order to adequately sample the upwind and downwind region.

Molnau, *et al.* (1980) showed how better estimates of mean annual precipitation occurred in a mountain watershed in Idaho when a higher concentration of gauges was assigned to zones with high precipitation variability. In their case, this resulted in a nonuniform distribution of gages as a function of elevation. They subdivided the total range of elevation (1097 to 2195 m) into four zones of equal elevation change. They found that 70 percent of the gauges should be in the higher two zones, and that 44 percent should be placed in the second highest zone. They were able to identify the highly variable zones because a very dense gauge network was installed and systematically reduced to obtain an optimum density and distribution.

The approach taken by Molnau, *et al.* (1980) in arriving at the best location for gauges by using data from a very dense network is supported by others. Corbett (1967) states that the best locations for a group of gauges can be determined only by operating a dense network long enough to provide a statistically sound data base. Eagleson (1967) supports this viewpoint and emphasizes that the gauges must be sited so as to randomly sample the catchment elevation.

In all of these gauge-distribution considerations, the proper installation of gauges in well-protected locations is the most important criterion. Keller (1972) concludes that it is better to estimate MAP for a winter season from fewer, but better sited gauges than from an entire gauge network which includes some poorly exposed gauges.

The present plan for gauge distribution in the Upper Colorado River Basin is as follows:

A. The highest priority will be to install gauges at well-protected sites, that is, clearings in the forest.

B. To the extent possible, place gauges in a uniform areal distribution.

C. Sample the full range of elevations (about 2500 to 3600 m) and aspects (upwind and downwind of barrier).

D. As possible, compensate for zones of higher precipitation variability by installing more gauges there. The highest terrain, often consisting of rugged mountain peaks, may have the highest variability. Unfortunately, such terrain may not offer suitable (well-protected) gauge sites. The highest elevations which have suitable sites will be instrumented. Most of the gauges will be placed at elevations above 2900 m (perhaps as many as 70 percent of the gauges in the network). Further analyses will be required to determine whether or not the results of Molnau, *et al.* (1980) which indicate that about 45 percent of the gauges should be placed in the second highest quartile of the range of elevations apply in the central Rocky Mountains. The mean winter isohyetal map for the region will assist in identifying regions of high precipitation variability.

A problem that requires further consideration is the monitoring of precipitation above tree line. Depending upon the areas chosen for the demonstration program, this could be a minor or a major problem.

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