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I. INTRODUCTION

Two main hypotheses underly this paper. First, weather modification has the capability of augmenting the water supply from high mountains by an increase of predominantly orographic precipitation. Second, the engineering operation in weather modification would be economically justified when the water supply measured by streamflow response is substantially increased.

One of the objectives in the statistical design of weather modification experiments and of their control techniques, is to minimize the confidence limits for any parameter used in evaluating their attainments. Design of experiments and their control techniques are judged partly by the time necessary for detecting changes in streamflow or precipitation.

Three levels of control may be used when evaluating various aspects and results of weather modification techniques, either for research purpose or for engineering operation: (a) Evaluation of phenomena produced in the atmosphere by weather modification (changes in cloud physics, precipitation at the cloud base, and evaporation of precipitation between the cloud base and the ground); (b) Evaluation of weather modification attainments at the ground surface through measurement of precipitation (rain and snow); and (c) Evaluation of weather modification attainments through streamflow response. The last evaluation level is the basis of this paper.

Attainments may be evaluated by pertinent streamflow information already available in a selected area. This approach does not assume that years are needed for the calibration of target and control basins for the

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evaluation of future weather modification attainment at the target basin. The basic material for control of future weather modification may be the streamflow data presently available. Previous general purpose streamflow gaging can be utilized to evaluate attainments by appropriate hydrologic and statistical techniques.

Proper quality assessment of streamflow data from main control gaging stations enables the selection and use of reliable streamflow data for the evaluation of weather modification attainment. The criteria of reliable data may be prescribed in advance by appropriate studies. Two steps are useful in preparing this data for evaluation: (a) Assessment of random errors, of systematic errors (inconsistency of data) and of non-homogeneity (man-made or nature-produced non-stationarity in data); and (b) Proper mathematical description of hydrologic time series of precipitation and runoff.

Results of weather modification experiments may be evaluated in a shorter period of time provided several drainage areas are simultaneously operated and a regional analysis approach is used. In other words, what is not available because of limited time may be partly obtained by expending experiments in space. A regional control of weather modification attainments through streamflow response would consist of concurrent operations and analyses of a sufficient number of drainage basins, both seeded and non-seeded. The main hypothesis in this approach is that the analysis of statistical evaluation parameters of streamflow for all gaging stations in a region may detect the produced changes in a shorter period of time than the analysis of the same parameters for individual basins or stations. The advent of fast digital computers makes the analysis of large amounts of regional hydrologic data tractable at a modest cost.

II. SELECTION OF VARIABLES AND OF THEIR PARAMETERS FOR WEATHER MODIFICATION EVALUATION.

Two basic selections in the evaluation of weather modification attainments, by using runoff or precipitation, are: (a) Selection of a variable or variables used in attainment evaluation; and (b) Selection of a variable parameter or parameters (in parametric method of control), or the selection of non-parametric control approach.

For the total period of investigation, T, there are N events of a

variable for either seeded or non-seeded events. If the variable relates to continuous units, t, of a time series, with the unit being a day, a month, a season or a year, then $N = T/t$ is the sample size. If the events occur from time to time, like individual storms, then n selected events in the total period, T, is a stochastic variable. The main difficulty in this second approach of assembling sample data is to obtain an objective definition of events to be selected as sample points. The third approach refers to a seasonal variable, like winter precipitation, wet season runoff and similar variables. The definition of the beginning and the end of seasons is usually a subject of controversy.

If $N = T/t$ with t very small, the sample looks very large. However, a description of a dependent time series by a stochastic hydrologic process contains an independent variable which has a larger variance than the dependent variable. The smaller t, usually the greater is the variance of that independent variable in comparison with the variance of the dependent variable. In some cases, like 1-day, 2-day, 3-day, ... , 10-day precipitation amounts, little or no difference may be found among them for the expression σ^2/N, with $N = T/t$, and σ^2 the variance of independent variable. A structure analysis of the hydrologic time series of precipitation and runoff gives an insight as to whether or not a small time unit, t, and large sample size, N, during a given period, T, produce any advantage in comparison with a larger time unit, t, and a smaller sample size, N. A common expectation is that a smaller time unit, t, which gives a large sample always produces a better discrimination of weather modification attainment then a greater value of t. Because this does not seem to be the case, it is not possible to select the best t value for a priori without special studies. Usually these studies are not undertaken before selecting variables in the statistical evaluation of weather modification attainment.

Nearly all precipitation and runoff gaging stations show a cyclic movement of a year and its harmonics. For seasonal or monthly values, after the harmonics are removed, the differences for precipitation show no significant time dependence, while those of monthly runoff show a water carryover dependence. These differences for daily precipitation show a dependence but it is much less than for the daily runoff.

Important parameters for the analysis of runoff in weather

modification control are: (a) Mean, because it determines the total water resources available; (b) Variance, because it measures the flow fluctuation, the need and the importance of flow regulation, and it determines the amount of storage capacities; and (c) Time dependence parameter or parameters, because they affect the needed storage capacity for a given degree of flow regulation. Weather modification is likely to change all three types of parameters.

For runoff, the following variables come into consideration for selection: daily, monthly, seasonal, and annual flow. The annual flow variable is by far the simplest to deal with because of the absence of cycles. Time dependence is a minimum and is often negligible. This is the case whenever the water carryover from one year to another is very small in comparison with mean annual flow. The seasonal, monthly, and daily flows have cycles of 12 months and often 6 months or smaller harmonics. The sequence of monthly flows may be mathematically described by a sum of a deterministic component-harmonics, and a stochastic component-an independent random variable with a moving average time dependence model [1].

III. MAXIMIZATION OF RIVER FLOW RESPONSE.

Attainments measured by river flow response to weather modification will be maximized if these two principles are properly applied:

(1) Drainage basin selected for experiments is entirely covered by weather modification operation. This would usually require a large area to be seeded with the drainage basin occupying the center of that area. Application of this principle insures that each part of the drainage basin contributes to the weather modification attainment.

(2) All storms which are seedable are seeded during the total time period, T, of weather modification attempts. The attainment is maximized by using every opportunity to increase the precipitation and runoff.

Assume that the runoff variable Q_t has a weather modification attainment ΔQ_t. The value $\overline{\Delta Q}_t/\overline{Q}_t$, with $\overline{\Delta Q}_t$ = mean attainment, and $\overline{Q}_t$ = mean runoff, is a measure of attainment. The detectability of changes in mean, produced by experiments, depends on: $\overline{\Delta Q}_t/\overline{Q}_t$; variance of Q_t; variance of errors in measuring and computing Q_t; and number of

independent events, N_{in}. The detectability in the change of var Q_t and of time dependence parameters of Q_t - series is also a function of the same factors which affect the change of mean. By applying the above two principles, the basic factor, $\overline{\Delta Q}/\overline{Q}$, will be maximized and with it the detectability of the change.

IV. DISCUSSION OF SOME CURRENT METHODS OF EVALUATING WEATHER MODIFICATION ATTAINMENT.

(a) Target and control basin approach. The traditional approach in selecting a target drainage basin and one, two or several adjacent control drainage basins, is not assumed to be an unquestionable and unique approach for the control of weather modification. A usual assumption is made that the dominating winds enable the seeding of the target area with no effect on the control area. This approach limits seeding operations on air masses which move along these dominated winds. It excludes several air masses moving with winds which cross both the target and control areas. By seeding only a restricted number of air masses the relative attainment is somewhat decreased. It is also difficult to avoid interdependence between the target and control areas as concerns the distribution of artificial ice nuclei.

The closer a control area is to a target area, the greater the correlation of their streamflow or precipitation, and the greater the interdependence between the target and the control areas in seeding operations and the ice nuclei carryover process. L. O. Grant [2] has found that in a drainage basin there is a carryover of ice nuclei from a previous seeding period to the next. If the next period (counted in days) is a non-seeded period, the carryover of ice nuclei makes it dependent on the history of previous seedings. This ice nuclei carryover is not only limited to time carryover, but it also works as a carryover in space.

(b) Randomization of time series approach. An independent sequence of seeded and non-seeded time units or storms over a target area is often considered as an attractive statistical approach for the control of weather modification experiments. Various statistical designs have been based on the assumption that the successive events are independent and that ice nuclei content per unit mass of air on successive days were independent from the preceding days. Both assumptions may not be fulfilled. Sequence of daily precipitation or even storms are

independent. Carryover of ice nuclei, if proven to be a significant factor, seriously questions the validity of this control approach when it is based on the independence of successive seeded and non-seeded short time units.

A time series of all potential weather modification events is divided in two time series (seeded and non-seeded days or events). Any detection of change in precipitation or runoff needs a double period of experimentation in comparison with the continuously seeded period, T. The main question is whether the randomization in time gives such an advantage as to compensate for a longer period necessary for experiments in that case.

It is an established fact that the main portion of moisture supply in high mountains is brought about, in many cases, by large storms that do not occur too frequently (the Rocky Mountains, the Sierra Nevada, and others). These large storms have an outlook for the greatest absolute weather modification attainment. A sufficiently long period of experimentation is necessary in order to obtain a reasonable number of these extreme events. This case is analogeous to sampling floods in the sequence of river flows. To obtain a reasonably accurate frequency of extreme floods, the period of observations should not be too short. Therefore, using the individual storms as sample points may not have an advantage in comparison with large time unit precipitations, such as a month, a season or a year. This is especially true for mountains in which the number of large storms per year is very small, and even the zero number of these storms per year has a high probability of occurrence. In the Rocky Mountains it has been noticed that dry years coincide with the absence of these large storms.

(c) Past records as control. Past records may be used very effectively to avoid the loss of time coming either because of the calibration of target basin - control basin relation, or because of the randomization of events into seeded and non-seeded series. Runoff data, which is generally more accurate than precipitation data, for the past periods of time, may be used in three directions: (1) As the non-seeded period for an individual river basin subject to weather modification; (2) As the simultaneous observations at the target basin for comparison with available data at the control river basin or basins; and (3) As data of an individual river basin in a set of seeded and non-seeded river basins.

The detectability of weather modification attainment may be accomplished in a shorter period by using past runoff data, a set of river gaging stations of seeded and non-seeded basins, and by maximizing the attainment in all seeded basins.

V. COMPARISON OF PRECIPITATION AND RUNOFF AS THE PHENOMENA USED FOR WEATHER MODIFICATION EVALUATION.

In the past, very little attention has been given to simultaneous using precipitation and runoff data in the evaluation of weather modification attainment. The bases of this technique is the pooling together of both precipitation and runoff information into a unique statistical evaluation technique. Either one or the other of the data has usually been considered. When both were used, they have been pursued parallely as two independent evaluation approaches.

Comparison of precipitation approach to streamflow approach in evaluation of weather modification attainment reveals the following:

(1) A good measurement of precipitation at a point for a given small time unit is subject to errors, ϵ_i, whose variance (var ϵ_i) is much greater than the variance of errors (var η_i) in a good measurement of streamflow;

(2) The total precipitation over an area for a time unit is determined by measurements of precipitation at several points through the areal sampling procedure. This produces errors with their sampling variance (var ψ_i). The sampling error involved can be very large for individual storms. The variances of errors of individual measurements and errors caused by areal sampling may be summed to obtain the total error variance, assuming that there is an indication that the two types of errors are independent. Both types of errors decrease with an increase of the time unit, t, to which the precipitation totals are referred;

(3) Streamflow measures the integrated effects on runoff over an area and also includes evaporation. If a mountain river basin is considered as a water producing unit, interest is much greater in the final produce of runoff than in precipitation;

(4) An increase in precipitation by weather modification usually results, percentagewise, in a greater increase of streamflow (fig. 1). Therefore, on an annual or seasonal basis, the evaluation of weather modification attainment becomes more readily discernable for runoff than for precipitation;

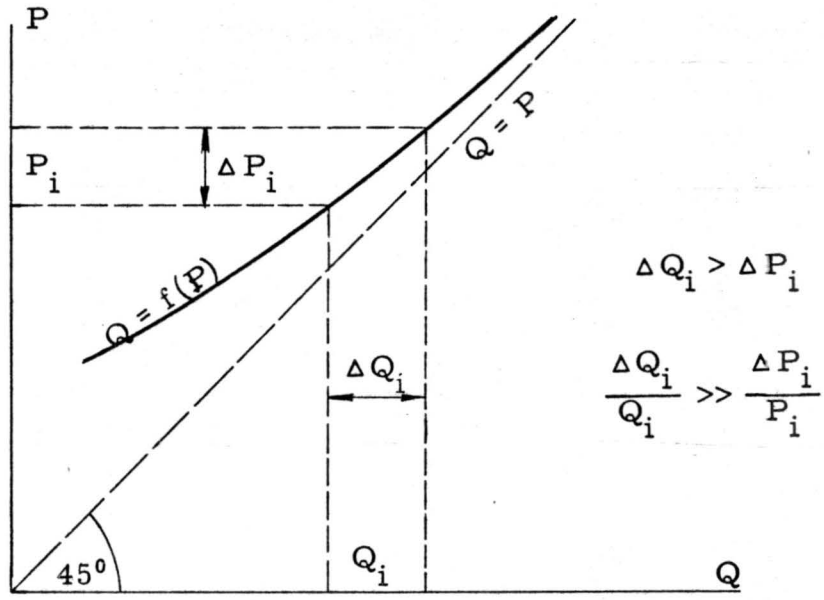

Fig. 1 General precipitation - runoff relationship for annual values, $Q = f(P)$. An increase in annual precipitation represents a larger absolute or relative increase in runoff.

(5) Because of water carryover in river basins, streamflow is less convenient for discriminating the effects of weather modification for variables obtained in small time units, such as days or durations of storms;

(6) The ice nuclei carryover in river basins affect the dependence of ice nuclei counts between successive precipitation events of small time units. As previously mentioned, for these small time units, like days or storm durations, the precipitation series have two types of dependence: (a) natural dependence of precipitation amounts; and (b) carryover of ice nuclei in time for ground generator approach to cloud seeding.

Assuming that the errors ϵ_i and ψ_i are independent among themselves and of P_t (precipitation variable), though $\overline{P}_t$ determines the order of their magnitude, that the error η_i is independent of Q_t (runoff variable) though $\overline{Q}_t$ determines its order of magnitude, then

the total variations in measured P_t and Q_t are

$$\text{var } P_t + \text{var } \epsilon_i + \text{var } \psi_i \tag{1}$$

and

$$\text{var } Q_t + \text{var } \eta_i \, . \tag{2}$$

For the reduced sample sizes (assuming N_1 and N_2 to be obtained under the assumption that time series of P_t and Q_t are randomized), the ratios

$$\frac{\text{var } P_t + \text{var } \epsilon_i + \text{var } \psi_i}{N_1} \tag{3}$$

and

$$\frac{\text{var } Q_t + \text{var } \eta_i}{N_2} \tag{4}$$

determine the confidence limits of $\overline{P}_t$ and $\overline{Q}_t$. As $\overline{\Delta Q}_t$ is expected to be greater than $\overline{\Delta P}_t$, and as in many cases, eq. (4) gives a smaller confidence limit than eq. (3), the detectability in runoff change may be obtained in a smaller time, T_o, than the detectability of change in precipitation. It is assumed that (var ϵ_i + var ψ_i) > var η_i, and that var P_t is of the same order of magnitude as var Q_t. If the ratios of eqs. (3) and (4) do not change appreciably with t, then the runoff becomes more attractive for the control of weather modification attainment than the precipitation. Figure 2 shows schematically these two cases with the change in $\overline{Q}_t$ more readily discernable.

VI. TYPES OF EVALUATION BY USING STREAMFLOW RESPONSE.

The following three types of streamflow response for the evaluation of weather modification attainment may be considered in the case of large scale operations or experiments:

(1) Comparison of statistical evaluation parameters of streamflow of the non-seeded with the seeded period at each main control gaging station for a given drainage basin;

(2) Comparison of all drainage basins subjected to weather

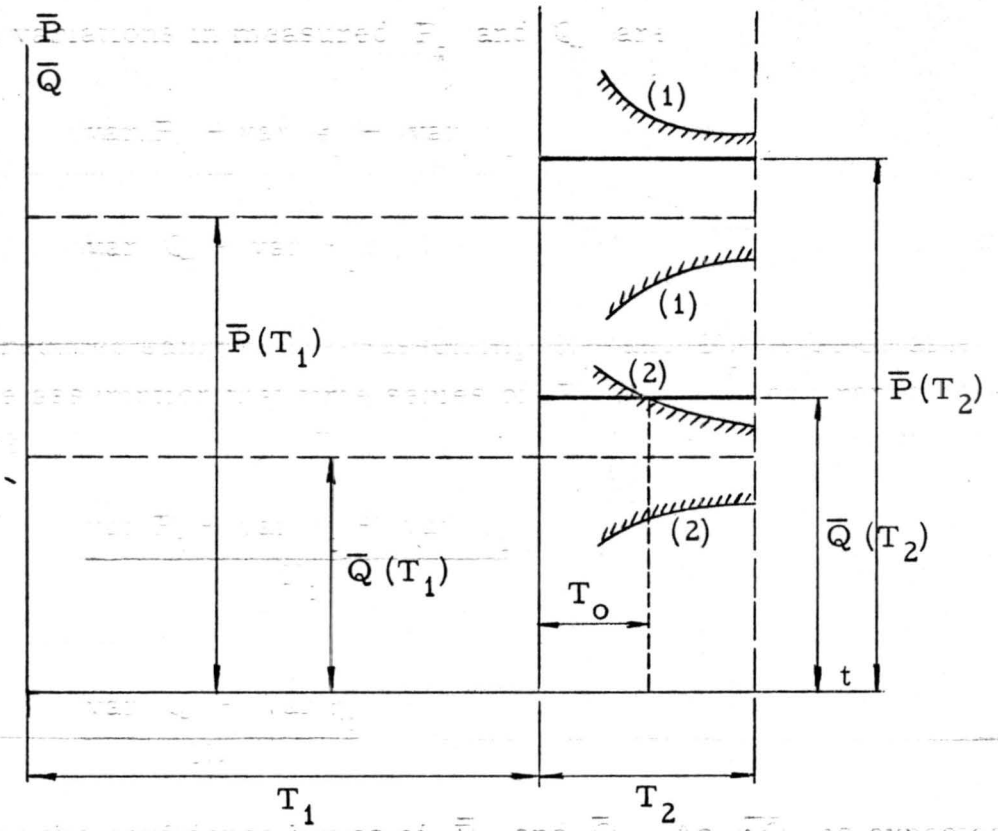

Fig. 2 As the total variance of mean annual runoff may be smaller than the total variance of mean annual precipitation, and as the relative increase of runoff is greater than for precipitation, the detection time for change, T_o, may be significantly smaller for runoff than for precipitation: T_1 = non-seeded period, T_2 = seeded period, $\overline{P}$ = mean annual precipitation, $\overline{Q}$ = mean annual runoff, (1) confidence limits for precipitation; and (2) confidence limits for runoff.

modification experiments with n drainage basins and the data of corresponding n gaging stations taken together as an aggregate of samples. This comparison is made between the non-seeded and the seeded period;

(3) Comparison of water yields and other parameters at seeded areas with adjacent non-seeded areas for the non-seeded and the seeded period.

In the first type of evaluation, m individual stations of m seeded drainage basins produce m testings of a given hypothesis

(significant runoff increase on a given probability level). The aggregate of final results becomes the information from which conclusions would be drawn concerning weather modification attainment. This approach may be used when a general design of experiments is based on simultaneous experiments on many drainage basins.

The second type of evaluation is based on a set of data of n gaging stations for n seeded drainage basins. Streamflow data for each station is described by appropriate parameters (mean, variance and others) both for the non-seeded and the seeded period. Then they are pooled together in a unique sample of statistical parameters, with proper weights. By testing for differences in properties of these parameters for the non-seeded and seeded periods, the sampling fluctuation of the main parameters for pooled data may be much less then for the individual stations. In pooling streamflow records of several stations into a unique sample, the concept of effective number of streamflow gaging stations may be a useful way of carrying out this type of evaluation. The effective number of stations is determined in such a way as to make data independent among a reduced number of stations.

The third type of evaluation consists of a comparison of water yield and other parameters between the seeded areas and the adjacent non-seeded areas. Period I refers to streamflow records obtained prior to seeding operations and Period II to the seeded time. If the relative specific yield of the seeded area for the non-seeded Period I is unity, and for the seeded Period II is $1 + a_o$, the difference a_o, represents both the sampling error and the seeded effect. The same relative values of specific yield are 1.00 and $1 + a_i$ for the adjacent regions 1, 2, ... m, with $i = 1, 2, \ldots m$. By studying the relationship among a_i for non-seeded areas and a_o for seeded areas, some general conclusions can be drawn as to whether the seeded area has had effects beyond sampling fluctuations of statistical parameters involved.

A study of statistical parameters relationships which describe the seeded area for both Periods I and II to the statistical parameters of adjacent non-seeded areas and the corresponding Period I or II represents a promising step toward discriminating the difference between the sampling error and the weather modification attainment. As the

directions of air mass movements will likely be systematically surveyed in a large experiment, a particular investigation would also include the study of statistical parameters of areas upstream and downstream of the seeded area. This approach would answer the problem whether the seeded area has affected the downwind areas.

Another approach for the seeding of drainage basins which merits an investigation is a special random selection of seeded basins. Assuming that the carryover of ice nuclei from one year to the next is relatively negligible for a drainage basin when this carryover is compared with the total amount of ice nuclei produced in a seeded year. If the following assumption is correct then a selection of m drainage basins to be seeded in a particular year out of a total of n basins (n much greater than m) can be made by a random sampling of basins. The equipment for cloud seeding and various observations connected with the seeding should be moved to the selected basins each year, except for those basins which are selected for consecutive years by this random sampling.

The seeded years at the seeded basins with a proper weight for basins will be a part of the sample of seeded years. The opposite is made for the non-seeded years at non-seeded basins. A comparison of these two samples may produce an answer to weather modification attainment in a shorter period than by other approaches.

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