SUITABILITY OF BASINS TO WEATHER MODIFICATION AND STATISTICAL EVALUATION OF ATTAINMENT

Final Report for FY 1966 and 1967

Prepared for:
Bureau of Reclamation
Office of Atmospheric Water Resources
Denver, Colorado

PROJECT SKYWATER

Under Contract No. 14-06-D-6007

by Dr. H. J. Morel-Seytoux

Associate Professor of Civil Engineering

July 1, 1968

HYDROLOGY PROGRAM
COLORADO STATE UNIVERSITY
Fort Collins, Colorado

Part 1

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ABSTRACT

Fundamentally the project was concerned with answering two questions:

(1) How surely can weather modification be considered responsible for observed increases in runoff?

(2) What makes a basin more suitable to a weather modification operation than another?

Tests were devised to answer the first question. Utilizing a target-control concept the tests indicate that six years or less would be sufficient to detect a 10% increase in seasonal runoff for about one-third of all gaged basins in the Upper Colorado River Basin.

Suitability criteria for both large water gain and rapid evaluation have been developed. Their application to the Upper Colorado River Basin point to three optimal zones of approximately 30 mile radius, centered around Red Mountain (half way between Silverton and Ouray,) Marble (or more precisely half way between Marble and Crested Butte) and Vail.

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A. INTRODUCTION

For convenience the Final Report to the Bureau of Reclamation has been divided into four parts. Part 1 is of general interest, whereas the other three parts report in detail some technical aspects of the work done. In the following, the word "report" refers to Part 1 of the Final Report.

The purpose of this report is:

1. To summarize the activities sponsored by the Bureau of Reclamation, Office of Atmospheric Water Resources, in the Hydrology Program of the Civil Engineering Department at Colorado State University, for the period July 1, 1966 to June 30, 1968, and

2. To focus attention on the results that may help the Bureau in planning future programs.

This report only summarizes the activities of the program. More complete information is available in already published papers or reports, or will be available in future publications. These publications are listed at the end of the report.

Section B of the report states the two major objectives of the program and the two functions it serves.

In order to meet the objectives it was necessary and convenient to divide the overall project into several main categories. Section C describes briefly the major divisions of the project. The reasons for these divisions and their relation to the objectives of the program are discussed.

Each of the following seven sections correspond to one major division of the research effort. Within each of these Sections (D through J) the problems are formulated, the difficulties are assessed, and the solution that was applied is briefly described. (Details of the work done can be found in the Colorado State University publications listed at the end of this report.)

B. OVERALL PURPOSE OF PROGRAM

The Colorado State University Hydrology program has two clearly defined objectives to serve two complementary functions. The two objectives are:

1. The development of a definite technique for evaluating the results of atmospheric water resources programs by mathematical and statistical analyses of streamflow records, and

2. The study of criteria, methods and procedures to be used in selecting drainage basins suitable for atmospheric water resources programs.

The program is to serve two functions:

1. To answer in theory the unsolved problems in order to meet the two objectives stated above, and

2. To provide the Bureau of Reclamation with an engineering capability to apply the theoretical results practically and specifically to the Bureau's programs in the Central Mountains Region.

C. WORK DIVISIONS AND RELATION TO OBJECTIVES

The first division in the project centered around the question of Statistical Evaluation of Weather Modification Attainments. Actually it is more accurate to say that this project was not so much concerned with the statistical evaluation of the attainment as with its statistical significance. In other words the effort was oriented toward the development of a test to accept or reject the null hypothesis at a given significance level. The null hypothesis is the hypothesis that the data samples, corresponding to the periods prior to seeding and during seeding, belong to one and the same population.

The difficulty in this evaluation can be traced to two main causes:

(a) the natural variability in the hydrologic cycle far exceeds the expected range of the increase induced by man, and

(b) the inaccuracy of the measurements may be of the same order of magnitude as the induced change.

It follows that a statistical technique must in some way eliminate the natural variability from the observed hydrologic data before a positive statistical inference can be made with regard to the effect of weather modification. In other words, the failure of a statistical test to detect a gain may be due either to an actual lack of effect of the weather modification operation or to the insensitivity of the test itself.

Because observed data upon which the tests were performed are somewhat in error, there is also a possibility that the statistical inference deduced from the data is wrong, that is, shows a statistically significant change when it should not and vice-versa. Therefore, the probability that errors in the measurement of the hydrologic data may lead to the wrong statistical inference must be calculated. Naturally, the greater the error in measurement, the greater the chance for a wrong statistical inference.

For these reasons the work effort was further divided into two research areas. One was concerned with the design of a sharp statistical test. The second consisted of a study of the type and magnitude of errors potentially incurred in the measurement and assembly of hydrologic data.

Next the suitability of a basin to atmospheric water reclamation programs was considered. In the experimental or the large-scale operational stage of the program, an operational site must be selected. Simply put, the question to be answered is: What makes one basin more suitable for a weather modification operation than another?

This question must be immediately qualified. What makes a basin suitable for different purposes? From a water resources point of view a basin is suitable if it responds to the maximum extent to a precipitation increase. From an evaluation point of view a basin is suitable if an increase in runoff can be detected in a minimum length of time. In addition meteorological suitability must also be defined. However, this criterion was beyond the objective and competence of the program, since the research effort was confined to hydrologic suitability from the point of view of evaluation and optimal water yield. But the criteria defining such suitability from the two points of view are not necessarily the same. Here also the research was divided into two research efforts:

(a) definition of a criterion of suitability for optimal water yield, and

(b) definition of a criterion of suitability for minimum time evaluation.

The simplest criteria were, respectively, a high specific yield and a low coefficient of variation for runoff. In practice these criteria have meaning only if they vary within broad limits, for otherwise the selection of basins for weather modification operations would be made solely on climatic and meteorologic considerations. Thus it was necessary to assess the range of variability of specific yield and coefficient of variation based on actual hydrologic data. This in turn led to the development of an exhaustive hydrologic data system for the Upper Colorado River Basin. The availability of this data system is desirable for many other reasons. It serves two functions: support for research, and development of a capability for systematic operational planning in that region. However, the first utilization of the data system has been the systematic computation of specific yield and coefficient of variation for the entire Upper Colorado River Basin.

Finally it is rather evident that the theoretical definition of a criterion is not very helpful unless it can be evaluated quantitatively. It is not sufficient to state that the criterion for suitability of a basin to weather modification is a high specific yield, that is, a high water yield per unit area of basin. One must also be able to determine this yield, even when the basin is not gaged. Thus work was done to derive, by a statistical method of prediction, equations for specific yield in terms of physiographic characteristics evaluated from maps for basins in the Upper Colorado River Basin.

In summary the research effort was divided into several categories with titles as listed below:

1. Statistical Methods of Evaluation of Attainment
2. Runoff Measurement Errors
3. Suitability of Basins for Optimal Water Yield
4. Suitability of Basins for Evaluation
5. Hydrologic Data System
6. Prediction of Specific Yield

Emphasis changed somewhat in the course of time. At first items 1 and 2 received most attention. Lately items 3 and 4 have been the center of interest. One reason is the fact that already a great deal is known about methods of evaluation of attainment. The literature is fairly abundant. On the other hand the question of suitability of basins has not been raised extensively and certainly has not been answered for use in the Upper Colorado River Basin. It was also clear that the initiation of a pilot program in this region was forthcoming. It was therefore decided to provide the Bureau with some rather crude but timely answers, helpful in the process of decision, rather than sophisticated, but belated, ones. It is also fairly evident that sophistication in statistical techniques reaches a point of diminishing returns which is not justified unless paralleled with judicious selection of variables to be tested and a thorough knowledge of the particular local hydrologic conditions. Professors Neyman and Scott, known statisticians, have themselves emphasized this point. We quote from page 342 of the Fifth Berkeley Symposium (1): "Turning to the very notion of precision, we wish to propose its measure, say N*, defined as the minimum number of experimental units which insures that, with the adopted level of significance α, with optimal randomization $\pi = 1/2$, with the given distributions of the observable variables, and with the use of the optimal $C(\alpha)$ test, the effect of seeding θ that is judged important to detect will be detected with the preassigned probability β.

$$"N^* = \frac{(2\tau/\ln\theta)^2}{\Delta^2}"$$

"It will be noticed that the numerator in this formula depends only on α, β and θ which the experimenter is at liberty to choose in conformity with his own opinions of the desired precision of the experiment. Contrary to this, the denominator Δ^2 depends on the conditions prevailing in the target area and on the design."

On page 337 (1) "it was suggested that the planning of a future experiment with weather control be preceded by an examination of historical climatological data collected for the contemplated general area of the experiment. This examination, covering a substantial period of time, perhaps as much as a decade, would have the purpose of establishing the most advantageous elements of the design of the prospective experiment, such as the definition of the observational unit, the desirable predictor variables and the details of the target."

In other words even the greatest statistical expertness cannot compensate for poor selection of site, test, and predictor variables of an experiment.

In the following sections the achievements of each work division are reviewed.

D. STATISTICAL METHODS OF EVALUATION OF ATTAINMENTS

One of the objectives of the program was to develop tests to decide whether or not seeding increased runoff in a given target area. One wants to ascertain with a small probability of error whether or not the sample of data collected under seeding operations and the sample of data collected under natural conditions belong to one and the same population. The null hypothesis is the hypothesis that the two samples belong to the same population.

Primarily because of the nature of the tested variable, e.g., yearly or seasonal runoff, these tests were developed for the purpose of evaluation of operational experiments rather than for the purpose of exploration to discover under which conditions seeding is or is not effective in increasing runoff amounts. The statistical techniques are not affected by the difference of purposes. However, the choice of the variable runoff makes the process of stratification of data less immediate than, say, with storm precipitation amounts. Similarly the fact that precipitation conducive to significant runoff falls primarily in the form of snow renders randomization ineffective except on a year to year basis.

The tests that were investigated fall under three main categories:

1. Two-samples tests (4)
2. Target-control tests (4)
3. Non-parametric tests (5)

The two-sample (historical sample prior to seeding, sample during seeding) tests are distressingly inefficient for runoff. This fact had already been well demonstrated for precipitation by several authors (2),(3). However, these simple tests point to the fact that the "size" (1) of the experiment or minimum number of years or seasons to detect a given increase in runoff varies like the square of the coefficient of variation of the target basin runoff. In the Upper Colorado River Basin this coefficient varies from 10 to 100%. In the extreme case the size of the experiment would vary a hundred fold. Most likely poor choice of a target area may entail a penalty of a factor of 5-10.

With annual runoff as the test variable this means decades versus years!

The target-control tests are much more discriminating. Roughly speaking the use of a control makes the target look as though it has an effective coefficient of variation much smaller than the actual one. The larger the coefficient of correlation between the target and the control, the smaller the apparent coefficient of variation of the target. As a result the detectability of a change in the target behavior is increased.

Given the regression line between target and control established on the basis of historical data prior to seeding, one tests whether the observed joint samples for the target and control belong to the joint historical population at a given confidence level. If the period of record prior to seeding is long enough it can be assumed with some confidence that the regression parameters are the population values. In this case it turns out that the observed statistic:

$$\chi_o^2 = \frac{\nu}{1-\rho^2}\left\{\left(\frac{\bar{\xi}-\bar{x}}{\sigma_x}\right)^2 - 2\rho\,\frac{(\bar{\xi}-\bar{x})(\bar{\eta}-\bar{y})}{\sigma_x \sigma_y} + \left(\frac{\bar{\eta}-\bar{y}}{\sigma_x}\right)^2\right\} \quad (1)$$

is distributed like Chi-square with two degrees of freedom. The meaning of the symbols appearing in the above formula is as follows:

ρ = population coefficient of correlation between the target and the control for the historical period (i.e., prior to seeding)

ν = number of years during which seeding took place

$\bar{x}$ = control mean over the historical period (assumed in this case equal to the population mean)

$\bar{y}$ = target mean over the historical period

σ_x^2 = population variance of control for the historical period

σ_y^2 = population variance of target for the historical period

$\bar{\xi}$ = control mean for the seeded period

$\bar{\eta}$ = target mean for the seeded period

This test is a great improvement over the two-samples tests. However, this test suffers from two drawbacks. First it is valid only if the estimates of the regression parameters differ slightly from the population values. To be more concrete let us consider as a target, the South Fork San Joaquin River gaged near Florence Lake, and the Merced

River gaged at Pohono Bridge as a control, for which 29 years of historical record are available. The limits of confidence for the historical target seasonal mean at the 95% confidence level expressed in percent of the sample mean are 86 and 114. For the control they are 86 and 114 also. The sample coefficient of correlation has the value 0.96. The limits of confidence (using Fisher's Z transform (6)) are 0.90 and 0.98. The possible error for the mean is not too serious. However, the error on the coefficient of correlation could be disastrous as ρ appears in the denominator of the expression for χ_o^2 in the form $1-\rho^2$. The values of χ_o^2 calculated on the basis of the sample estimate and of the lower limit of confidence are essentially in the ratio 2 to 1.

As the number of years of record increase, the limits of confidence narrow, but it is better not to count on it. There are only 93 stations presently operating in the Upper Colorado River Basin, out of 820, that have 30 or more years of record.

The second drawback is that the abnormality of the seeded joint sample may be due to the abnormal behavior of the control rather than that of the target.

Both difficulties can be eliminated by the use of another test, the target-control conditional Student's t-test. This test does not assume that the population regression parameters for the historical records are known, and it tests the normality or abnormality of the target, given the behavior of the control, normal or otherwise. By application of the generalized maximum-likelihood ratio method (7) it turns out that the observed statistic:

$$t_o = \frac{\dfrac{\sqrt{n+\nu-3}\ \{(\overline{\eta}-\overline{y}) - \dfrac{(\overline{\xi}-\overline{x})}{\Delta}\ (\sum_{i=1}^{n} a_i \Delta y_i + \sum_{j=1}^{\nu} \alpha_j \Delta\eta_j)\}}{\left[\dfrac{1}{n} + \dfrac{1}{\nu} + \left(\dfrac{\overline{\xi}-\overline{x}}{\Delta}\right)^2\right]^{1/2}}}{\left[\sum_{i=1}^{n} \Delta y_i^{\,2} + \sum_{j=1}^{\nu} \Delta\eta_j^2 - \left(\sum_{i=1}^{n} a_i \Delta y_i + \sum_{j=1}^{\nu} \alpha_j \Delta\eta_j\right)^2\right]^{1/2}} \qquad (2)$$

is distributed like Student's t with $n+\nu-3$ degrees of freedom. The meaning of the symbols is as follows:

n = years of historical record

ν = years of seeding

x_i = control data point prior to seeding

ξ_j = control data point during seeding

y_i = target data point prior to seeding

η_j = target data point during seeding

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad \overline{\xi} = \frac{1}{\nu}\sum_{j=1}^{\nu} \xi_j \qquad \overline{y} = \frac{1}{n}\sum_{i=1}^{n} y_i \qquad \overline{\eta} = \frac{1}{\nu}\sum_{j=1}^{\nu} \eta_j$$

$$\Delta x_i = x_i - \overline{x} \qquad \Delta y_i = y_i - \overline{y} \qquad \Delta \xi_j = \xi_j - \overline{\xi} \qquad \Delta \eta_j = \eta_j - \overline{\eta}$$

$$a_i = \frac{\Delta x_i}{\Delta} \qquad \alpha_j = \frac{\Delta \xi_j}{\Delta}$$

$$\Delta^2 = \sum_{i=1}^{n} \Delta x_i^{\,2} + \sum_{j=1}^{\nu} \Delta \xi_j \, .$$

The expression for t_o appears rather formidable but is really easily calculated by simple arithmetic operations on the data, which have been programmed for the computer. (See subroutine TARCOT description in Part 4.)

The power (in the statistical sense, i.e., 1 - probability of error of type II) of the above test was not calculated. However, numerical experiments performed on the data for the South Fork San Joaquin and Mono Creek as targets, and the Merced River as control, show that the test is effective in detecting an increase in runoff in a relatively few years. Table 1 summarizes the results of various calculations. The runoff data are listed in Appendix B, Table 13.

In particular Table 1 shows that the runoff data must be corrected for engineered modifications of the natural flow. This is well demonstrated by the results of lines 1 and 7. The test fails to detect

TABLE 1

RESULTS OF TARGET-CONTROL STUDENT'S t-TEST

TARGET: South Fork San Joaquin - near Florence Lake (GS 11-2300)

CONTROL: Merced River at Pohono Bridge (GS 11-2665)

Line number	Used years of seeding	Runoff Variable Yearly	Runoff Variable Seasonal	Corrected for storage and diversion	t	Significance	Most likely increase in %	Maximum probable increase at 95%
1	15		$\sqrt{R}$	No	1.53	No		
2	15	$\sqrt{R}$		No	1.98	No		
3	8	R		Yes	1.45	No		
4	15	R		Yes	1.87	No		
5	4		R	Yes	1.76	No		
6	5		R	Yes	2.34	95%	9.7	17
7	5		$\sqrt{R}$	Yes	2.60	98%		
8	8		R	Yes	3.02	99%	10.7	15
9	10		R	Yes	2.61	99%	8.2	14
10	15		R	Yes	3.53	99%	10.1	16
11	15		$\sqrt{R}$	Yes	3.71	99%		
12	16		R	Yes	3.74	99%	10.5	16
13	16		$\sqrt{R}$	Yes	3.96	99%		

Legend: $\sqrt{R}$ means that test is based on the square root of runoff data.

Calculations are based on the data as published by the U. S. Geological Survey in their water supply papers 1315A, 1735 and yearly water supply papers for the years 1961-1966. Part of the flow is diverted from the river above the gaging point through the Ward tunnel (GS 11-2295). The flow is regulated above the gaging point by the presence of the Florence Lake dam (GS 11-2296).

Station number	Old G.S. number	New G.S. number
South Fork San Joaquin	11-064	11-2300
Florence Lake	11-062	11-2296
Ward Tunnel	11-063	11-2295
Merced River	11-124	11-2665

a significant increase in runoff after 15 years of operation, when uncorrected seasonal runoff is used (line 1 of Table 1). The same test on the other hand shows a highly significant increase after only five years of operation, when corrected seasonal runoff is used as the test variable (line 7 of Table 1). It also shows the importance of selecting the proper variable to be tested. Seasonal (March-August) runoff is much more representative of the effect of seeding than yearly runoff. With seasonal runoff the size of the experiment is reduced from more than 15, to 5 years, as is shown by comparison of lines 4 and 6 of Table 1.

The table also gives the most likely increase in percent. It is obtained by taking the difference between the mean historical target value calculated from the historical regression line, and the mean seeded period target value calculated from the new regression line, i.e., defined over the years of seeding only. Both quantities are evaluated at the control mean value over both the historical and the seeded periods. Because the new regression line is based on relatively few years of record, the estimate of the new population target mean can be seriously in error. Substituting for the estimate of the target mean an upper limit of confidence at 95% level in the previously mentioned difference, one obtains the "maximum probable increase." In the respective columns, line 12 of Table 1 gives the values 10.5 and 16%. This means that after 16 years of seeding the best estimate of how much seeding increases runoff on the average, based on observed data, is 10.5%. Because of the variability of the increase from year to year, this estimate could be in error. The interpretation of the figure 16% in the last column is as follows: there is only a 5% chance that the actual long-term average increase will be larger than 16%, given that it was observed to be 10.5% over a period of 16 years. Of course it could be smaller. It must also be kept in mind that the 10.5% and 16% figures apply to the drainage basin of the South Fork San Joaquin above Florence Lake under the chosen rules of operations and the state of technological knowledge prevailing during these sixteen years. For a different basin, different rules of operation, and an improved state of the art, the results may be quite different. The percentage increase also depends on the size of the basin and particularly upon the fraction of it that lies above the 9000-10,000 feet elevation. The purpose of the numerical experiments summarized in Table 1 is not to demonstrate the effectiveness of seeding, but rather to illustrate the effectiveness of the target-control conditional Student's t-test at detecting it.

The question is sometimes raised that the tests may not be valid because the joint bivariate distribution of the target and control populations is not normal. For runoff the distribution that best fits the observed frequencies is usually the normal one (9). Sometimes the normal distribution more closely approximates the frequencies when the data have been first subjected to a square root transformation or a logarithmic one. Table 2 shows that in practice the outcome is hardly affected. In statistical terms one can say that the test is "robust."

Tables 3, 4, and 5 summarize a few more calculations that illustrate the inefficiency of the two-sample tests and the possible danger involved in using the chi-square test. However, when the sample estimates are used (1st line of tabulated data) the results parallel those of the t-test very closely.

A non-parametric test was also developed (5) based on the theory of runs (7), (10). It appears promising. However, its power was not calculated and when applied to a set of data it showed no significance. The value of that particular test remains an open question.

TABLE 2

INFLUENCE OF DATA TRANSFORMATION ON THE RESULSTS OF THE TARGET-CONTROL CONDITIONAL STUDENTS' t-TEST

TARGET: South Fork San Joaquin

CONTROL: Merced River at Pohono Bridge

Years of seeding: 15
Years of record prior to seeding: 29
Data: Various transformations of seasonal runoff from reference 8

Target-control conditional t-test results

Type of Transformation	t-statistic	Significance
Square	3.22	99%
None	3.80	99%
Square root	4.06	99%
Fourth root	4.16	99%
Logarithmic	4.23	99%

TARGET: Mono Creek

CONTROL: Merced River at Pohono Bridge

Type of Transformation	t-statistic	Significance
Square	1.78	No significance
None	2.08	95%
Square root	2.20	95%
Fourth root	2.25	95%
Logarithmic	2.29	95%

Values of t for significance at 95% = 2.02
98% = 2.42
99% = 2.71

TABLE 3

RESULTS OF TWO-SAMPLE AND CHI-SQUARE TEST USING SEASONAL RUNOFF DATA

TARGET: South Fork San Joaquin

Years of seeding: 15
Years of record prior to seeding: 29
Data: Seasonal runoff as given in reference 8

Target sample mean before seeding = 194
Limits of confidence of mean at 95% level: 168-220
Unbiased standard deviation = 67
Coefficient of variation = 0.34

Observed u-statistic: 1.20 no significance
Observed t-statistic: 0.89 no significance

CONTROL: Merced River at Pohono Bridge

Regression sample coefficient of correlation = 0.964
Limits of confidence at 95% level: 0.92-0.98
Control sample mean before seeding: 375
Limits of confidence at 95% level: 326-423

χ^2 Test Results Based on Various Combinations of Parameters

	Target Mean	Control Mean	Coefficient of Correlation	χ^2	Significance Level
Sample	194	375	0.964	22.2	99%
	220	423	0.92	11.2	99%
	220	326	0.92	19.7	99%
	168	423	0.98	542	99%

Value of χ^2 for significance at 99% level of confidence = 9.2

Most probable % increase = $\frac{214-194}{194}$ = 10.3%

TABLE 4

RESULTS OF TWO-SAMPLE AND CHI-SQUARE TEST
USING SQUARE ROOT OF SEASONAL RUNOFF DATA

TARGET: South Fork San Joaquin

Years of seeding: 15
Years of record prior to seeding: 29
Data: Square root of seasonal runoff as given in reference 8

Target sample mean before seeding = 13.7
Limits of confidence at 95% level: 12.7-14.7
Unbiased standard deviation: 2.5
Coefficient of variation = 0.18

Observed u-statistic = 1.08 no significance
Observed t-statistic = 0.82 no significance

CONTROL: Merced River at Pohono Bridge

Regression sample coefficient of correlation = 0.970
Limits of confidence at 95% level: 0.93-0.99
Control sample mean before seeding = 19.1
Limits of confidence at 95% level: 17.7-20.4

χ^2 Test Results Based on Various Combinations of Parameters

	Target Mean	Control Mean	Coefficient of Correlation	χ^2	Significance Level
Sample	13.7	19.1	0.97	24.5	99%
	14.7	20.4	0.93	12.4	99%
	12.7	20.4	0.99	637	99%

Value of χ^2 for significance at 99% level of confidence = 9.2

TABLE 5

RESULTS OF TWO-SAMPLE AND CHI-SQUARE TESTS USING SEASONAL RUNOFF DATA

TARGET: Mono Creek

Years of record prior to seeding = 29
Years of seeding = 15
Data: Seasonal runoff as given in reference 8

Target sample mean before seeding = 94
Limits of confidence at 95% level: 81-108
Unbiased standard deviation = 35
Coefficient of variation = 0.37

Observed u-statistic: 0.48 no significance
Observed t-statistic: 0.37 no significance

CONTROL: Merced River at Pohono Bridge

Regression sample coefficient of correlation = 0.955
Limits of confidence at 95% level: 0.90-0.98
Control sample mean before seeding = 382
Limits of confidence at 95% level: 327-438

χ^2 Test Results Based on Various Combinations of Parameters

	Target Mean	Control Mean	Coefficient of Correlation	χ^2	Significance Level
Sample	94	382	0.955	6.6	95%
	108	438	0.90	5.2	No
	108	327	0.90	25.9	99%
	81	438	0.98	341	99%

Most probable % increase = $\frac{99-94}{94}$ = 5.3%

E. SUITABILITY OF BASINS FOR EVALUATION

For statistical evaluation of a highly localized cloud seeding experiment probably the most important consideration in the selection of a basin is the number of years, on the average, that will be required to detect a significant change, say in runoff, at a given confidence level. The criterion depends, among other things, on the choice of the variable selected to test the hypothesis, on the type of statistical test, and on the design of the experiment. One can define some marginal criteria to determine the relative suitability of many potential basins if the type of statistical test and the design of the experiment are not known a priori or, in other words, the criterion of suitability for the selected hydrologic variable, e.g., yearly runoff, everything else being the same. In this particular instance the most suitable basins are the ones that have the lowest coefficient of variation.

This criterion is derived from the two-sample u-test, assuming that the effect of seeding is to increase the natural mean by a certain percentage κ. Significance is achieved by the u-test if the observed statistic:

$$u_o = \frac{\kappa \mu \sqrt{N}}{100\sigma} \geq u_\alpha (= 1.96 \text{ at the 95\% level})$$

where κ is the expected percentage increase, N is the number of years of seeding, μ is the natural mean, and σ the standard deviation. From the above expression the minimum value of N for significance is obtained. Everything else being the same (i.e., confidence level, expected percentage increase by seeding, etc.) this number increases as the square of the coefficient of variation (ratio of standard deviation over mean).

This criterion is simple enough that it can be calculated for all gaged basins in the Upper Colorado River Basin, thereby providing the means of eliminating a great number of basins from further consideration, since the number of years increases as the square of this coefficient. This calculation has been carried for yearly runoff and two seasonal runoffs corresponding to the months March through August and April through July.

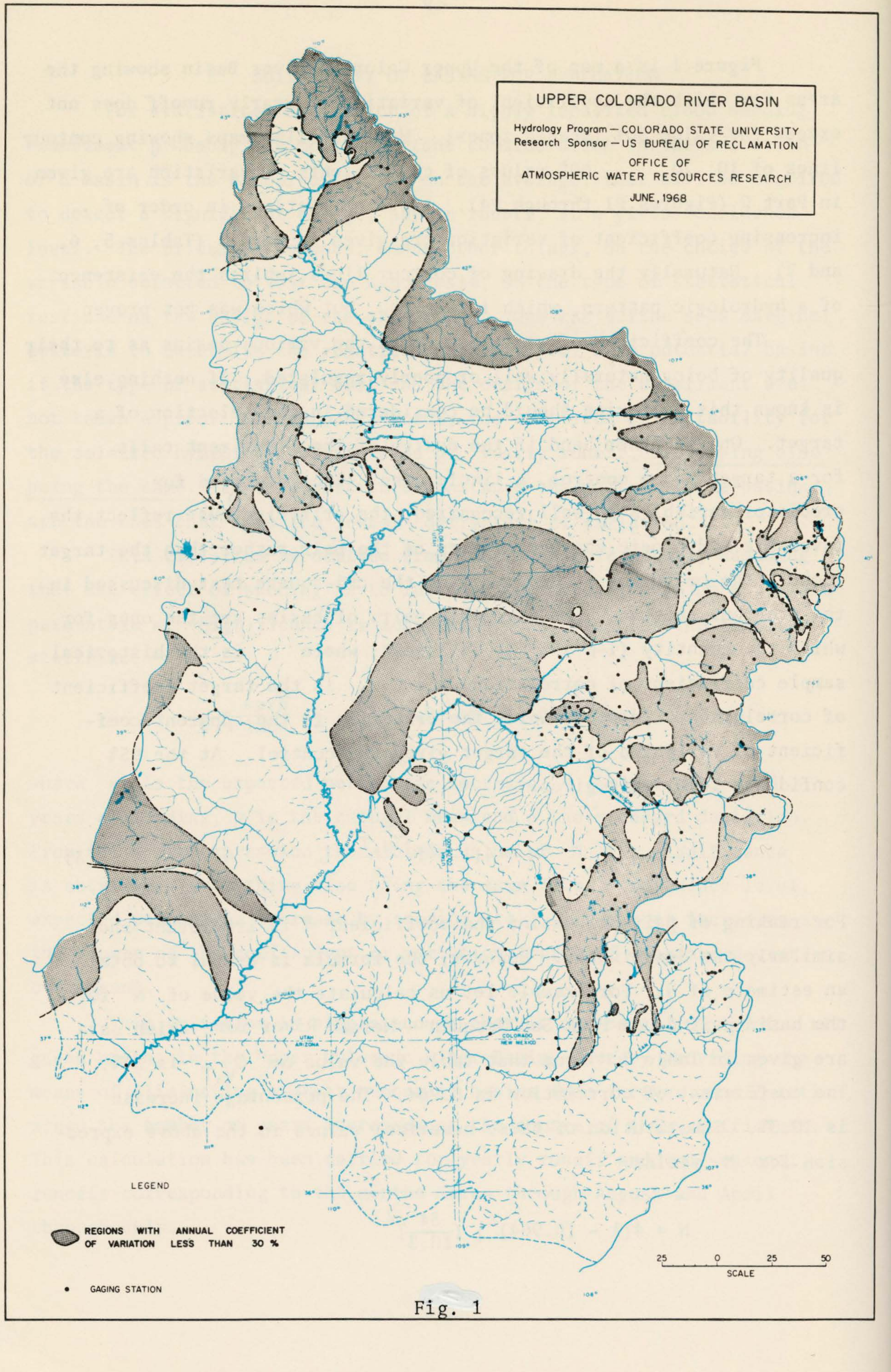
Figure 1 is a map of the Upper Colorado River Basin showing the areas for which the coefficient of variation of yearly runoff does not exceed the value 30% (shaded zones). More detailed maps showing contour lines of 10, 20, ..., 60% values of coefficients of variation are given in Part 2 (Figures P1 through P4). Lists of stations in order of increasing coefficient of variation are given in Part 3 (Tables 5, 6, and 7). Naturally the drawing of contour lines implies the existence of a hydrologic pattern, which is assumed, but which was not proven.

The coefficient of variation ranks the various basins as to their quality of being naturally well or poorly regulated. If nothing else is known this criterion should be considered in the selection of a target. On the other hand if the design of the experiment calls for a target and a control, a likely case, since the need for predictor variables is well recognized, the criterion must reflect the favorable hydrologic characteristics of the pair rather than the target alone. The criterion is deduced from the chi-square test discussed in the previous section. The favorable pairs of basins are the ones for which the quantity $(1-\rho^2)\ C^2_{v,T}$ is lowest, where ρ is the historical sample coefficient of correlation, and $C_{v,T}$ is the target coefficient of correlation. In other words the criterion is the apparent coefficient of variation of the target given the control. At the 95% confidence level this gives:

$$N = 4(1-\rho^2)\ \frac{C^2_{v,T}}{\kappa^2} \quad . \qquad (3)$$

For ranking of pairs of basins the coefficient 4 is irrelevant and similarly the denominator. However, the formula is useful to obtain an estimate of N. For example let us calculate the value of N for the basin pair South Fork San Joaquin - Merced River for which data are given in Table 3. From that table the value of $C_{v,T}$ is 34%. The coefficient of correlation is 0.964. The percentage increase is 10.3%. Substitution of these numerical values in the above expression for N yields:

$$N = 4[1 - (0.964)^2]\ (\frac{34}{10.3})^2$$


UPPER COLORADO RIVER BASIN
Hydrology Program — COLORADO STATE UNIVERSITY
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OFFICE OF
ATMOSPHERIC WATER RESOURCES RESEARCH
JUNE, 1968
LEGEND
REGIONS WITH ANNUAL COEFFICIENT OF VARIATION LESS THAN 30 %
GAGING STATION
25 0 25 50
SCALE
WYOMING
UTAH
COLORADO
ARIZONA
NEW MEXICO
GREEN RIVER
COLORADO RIVER
SAN JUAN
DOLORES
GUNNISON RIVER
YAMPA RIVER

Fig. 1

or N = 4 because N must be an integer.

Carrying the same calculations for the pair Mono Creek - Merced River (data in Table 5) one obtains a value for N of 17. The actual application of the target control conditional Student's t-test required 5 and 15 years respectively. These two sample calculations indicate that under actual seeding conditions equation (3) provides a good estimate of the number of years needed for significance. Figure 2 illustrates the variations of N with the coefficient of correlation and the coefficient of variation for an assumed 10% increase due to seeding. The use of the chart is straightforward. Suppose the coefficient of correlation between target and control is 0.948 and the target coefficient of variation has the value 22%. For these values of the abscissa (0.948) and of the parameter (22%) the chart reads N = 2. Suppose the percentage increase for the basins considered is expected to be about 5%. Because the chart was calculated for an expected increase of 10% the value N read from the chart must be modified. Specifically it must be multiplied by $(\frac{10}{5})^2 = 4$. Thus in this example the number of years for significance would be 2 x 4 = 8. In summary the chart provides means of estimating the value of N given the coefficient of correlation between target and control and the coefficient of variation for the target. Previous calculations based on actual seeding operational data from the Southern Sierra Nevada have demonstrated the value of the estimate of N from the chart. However our primary interest is in the Upper Colorado River Basin. Therefore calculations were performed for a few stations in this basin to have an idea of what could be expected if seeding operations were conducted in the area. In particular the expected number of years to detect a 10% increase at the 95% level of significance was calculated. The results are shown in Table 6.

It may happen that several pairs of basins will have the same coefficient of correlation, though based in some instances on very few years of historical record and in other cases on many. The reliability of the estimate of the coefficient of correlation decreases with the decrease in the number of years of record. It therefore appears meaningful to differentiate among gaging stations on the additional basis of

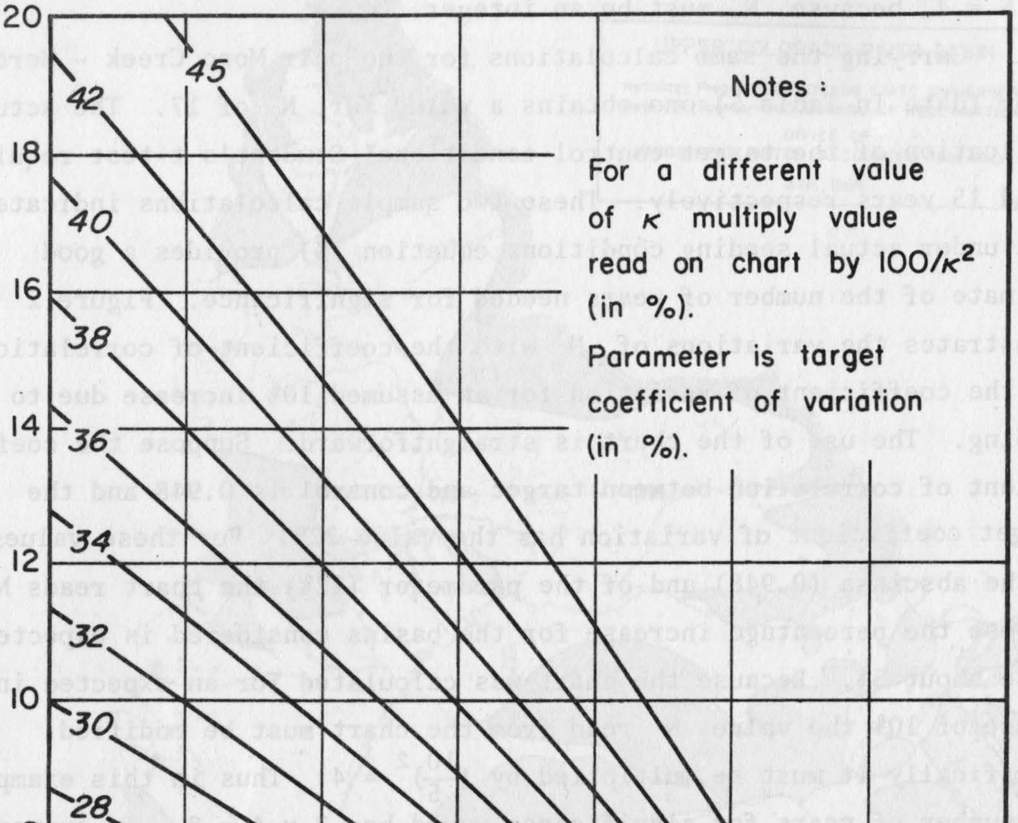


Fig. 2 Number of years (or seasons) to detect a 10 % increase.

TABLE 6

EXPECTED NUMBER OF YEARS TO DETECT A 10% INCREASE AT THE 95% LEVEL OF SIGNIFICANCE FOR A FEW PAIRS OF TARGET-CONTROL STATIONS IN THE UPPER COLORADO RIVER BASIN

TARGET					CONTROL			TARGET-CONTROL PAIR		
CSU Number	USGS Station Name	Drainage (sq mi)	Elevation (ft)	Coefficient of Variation (%)	CSU Number	Station Name	Drainage	Years of Common Record	Coefficient of Correlation (%)	Years Needed for Significance at 95% confidence level
1073440	Junction Creek near Durango, Colorado	26	7045	36	1073448	Hermosa Creek near Hermosa, Colorado	172	5	85	14
1073480	Animas River at Howardsville, Colorado	56	9617	27	1073448	Hermosa Creek near Hermosa, Colorado	172	25	90	6
1278800	Dolores River below Rico, Colorado	105	8422	45	1073448	Hermosa Creek near Hermosa, Colorado	172	13	98	4
1590000	Roaring Fork at Glenwood Springs, Colorado	1460	5720	33	1600000	Colorado River at Glenwood Springs, Colorado	4560	58	89	9
1594236	North Fork Fryingpan near Norrie, Colorado	41	8400	30	1594260	Fryingpan River at Norrie, Colorado	90	23	91	7

the available number of years of record. This can be done by introducing a criterion number

$$Nc = D(1 - \rho_L^2)\, C^2_{v,T}$$

where D is any suitable scale constant. The criterion number is deduced from equation (3) by substituting for the sample coefficient of correlation ρ its lower limit of confidence at 95% level, ρ_L, which depends on the number of years of record. Figure 3 illustrates the variation of this quantity Nc as a function of ρ and n, (number of years of historical record, assuming a coefficient of variation of 30% and an increase of 10%).

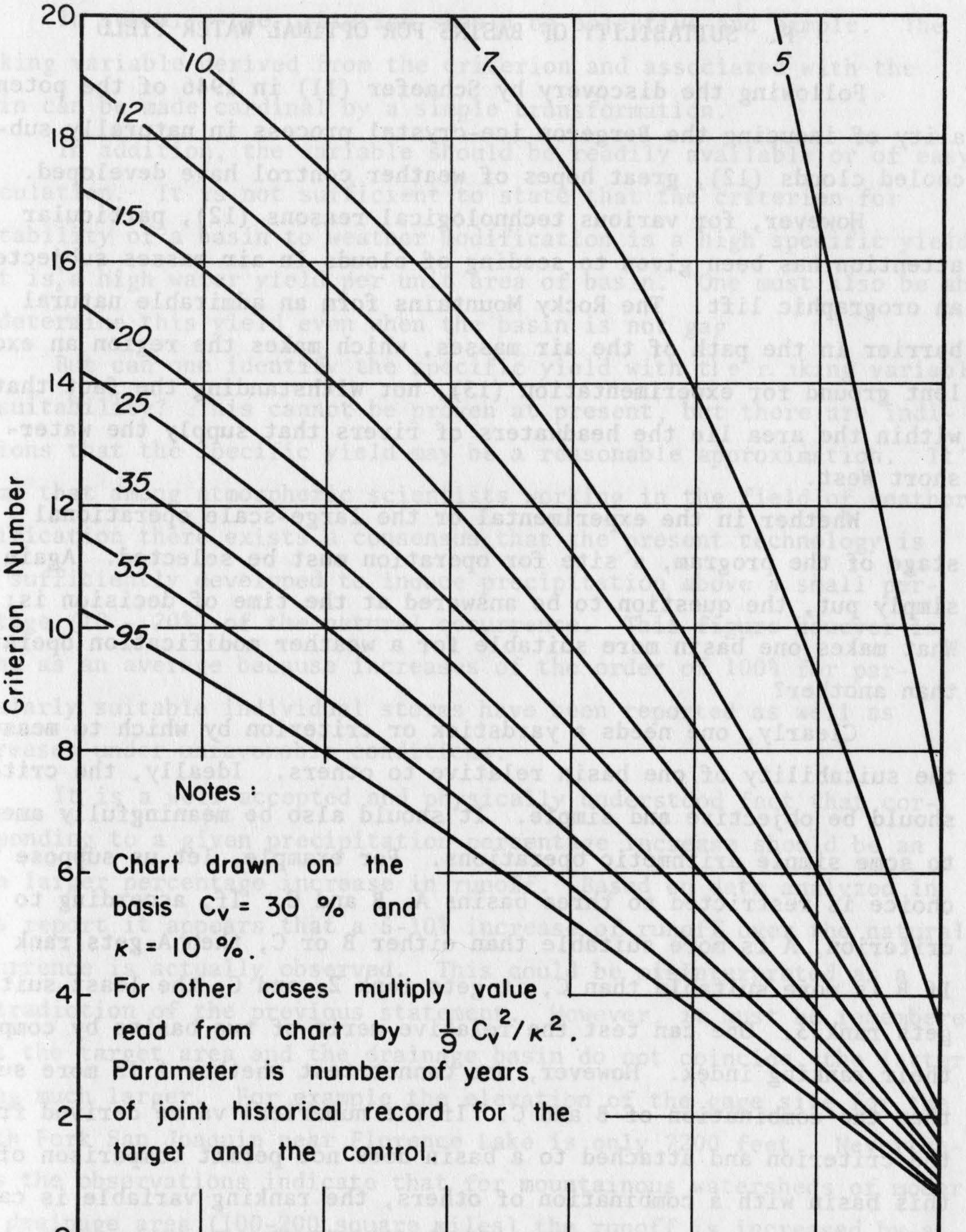


Fig. 3 Criterion number to rank basins as to suitability for evaluation.

F. SUITABILITY OF BASINS FOR OPTIMAL WATER YIELD

Following the discovery by Schaefer (11) in 1946 of the potentiality of inducing the Bergeron ice-crystal process in naturally subcooled clouds (12), great hopes of weather control have developed.

However, for various technological reasons (12), particular attention has been given to seeding of clouds in air masses subjected to an orographic lift. The Rocky Mountains form an admirable natural barrier in the path of the air masses, which makes the region an excellent ground for experimentation (13), not withstanding the fact that within the area lie the headwaters of rivers that supply the water-short West.

Whether in the experimental or the large-scale operational stage of the program, a site for operation must be selected. Again, simply put, the question to be answered at the time of decision is: What makes one basin more suitable for a weather modification operation than another?

Clearly, one needs a yardstick or criterion by which to measure the suitability of one basin relative to others. Ideally, the criterion should be objective and simple. It should also be meaningfully amenable to some simple arithmetic operations. For example, let us suppose the choice is restricted to three basins A, B and C. If, according to the criterion, A is more suitable than either B or C, then A gets rank 1. If B is more suitable than C, it gets rank 2, and C, the least suitable, gets rank 3. One can test the relative merit of two basins by comparing their ranking index. However, one cannot test whether A is more suitable than the combination of B and C. If the numerical value derived from the criterion and attached to a basin does not permit comparison of this basin with a combination of others, the ranking variable is called ordinal (14). If it does, it is called cardinal. To the extent that the original question: "What makes one basin more suitable than another?" may be modified into the following: "What makes one group of basins more suitable than another group?", it is important that the ranking variable should be cardinal or that another ranking variable be easily deduced from it and have the cardinal property.

In summary, the criterion should be objective and simple. The ranking variable derived from the criterion and associated with the basin can be made cardinal by a simple transformation.

In addition, the variable should be readily available or of easy calculation. It is not sufficient to state that the criterion for suitability of a basin to weather modification is a high specific yield, that is, a high water yield per unit area of basin. One must also be able to determine this yield even when the basin is not gaged.

But can one identify the specific yield with the ranking variable of suitability? This cannot be proven at present, but there are indications that the specific yield may be a reasonable approximation. It seems that among atmospheric scientists working in the field of weather modification there exists a consensus that the present technology is not sufficiently developed to induce precipitation above a small percentage (10 - 20%) of the natural occurrence. This figure however is meant as an average because increases of the order of 100% for particularly suitable individual storms have been reported as well as decreases under unfavorable conditions.

It is a well accepted and physically understood fact that corresponding to a given precipitation percentage increase should be an even larger percentage increase in runoff. Based on data analyzed in this report it appears that a 5-10% increase of runoff over the natural occurrence is actually observed. This could be misinterpreted as a contradiction of the previous statement. However, it must be remembered that the target area and the drainage basin do not coincide, the latter being much larger. For example the elevation of the gage site for the South Fork San Joaquin near Florence Lake is only 7200 feet. Nevertheless the observations indicate that for mountainous watersheds of moderate drainage area (100-200 square miles) the runoff is increased by a small percentage over the natural occurrence of the order of 5-10%. Naturally, integrated over large areas the small increase is of tremendous economic significance.

The consensus seems also to be that the perturbation introduced by man does not propagate beyond the narrowly localized region of operations. In other words, it can be assumed that operations in a basin will hardly affect the natural process in the neighborhood. Based on these opinions, one can formulate as a first approximation the following postulates:

(a) The specific water yield of a basin is not affected by operations of weather modification over an adjoining basin (assuming, of course, that the operations of seeding can be accurately controlled in space), and

(b) The increase in precipitation by cloud seeding is directly proportional to the basin's natural yield. Inasmuch as statements (a) and (b) are reasonably true, specific yield is a reasonable approximation for the ranking variable. It does not have the previously described cardinal property that yield has.

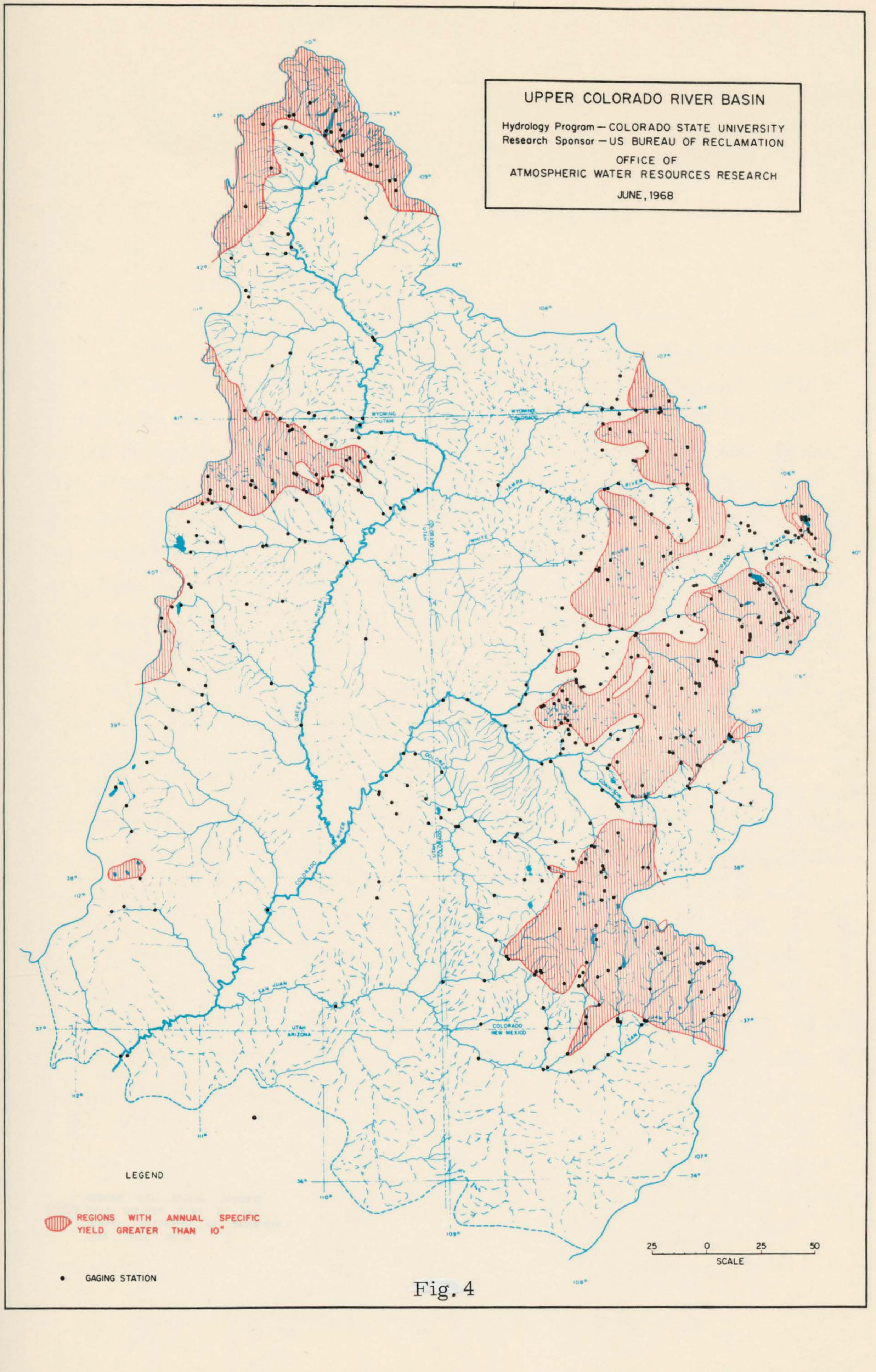
Again the discussion would be academic if specific yield was essentially uniform throughout the basin. However, this is far from being the case. Specific yield varies from practically zero to a maximum around 40 inches.

Specific yield (in inches) has been calculated for all gages in the Upper Colorado River Basin. Figure 4 is a map of the Basin showing the areas for which the annual specific yield exceeds 10 inches (shaded zones). More detailed maps showing contour lines of equal specific yield are given in Part 2 for annual, semi-annual and 4 months specific yield (Figures P5 through P8).

Specific yield in all these maps does not correspond to a local value except for regions of high elevation, rather it is an average value for the entire drainage area upstream of the gage.

By overlay of the contour lines of specific yield and coefficient of variation of a given hydrologic test variable one can delineate regions that are optimally suited for evaluation and yield augmentation. Figure 5 shows such regions (shaded zones), optimality being defined in this instance as the combination of an annual specific yield in excess of 10 inches and a coefficient of variation less than 30%. More detailed overlays showing the superposition of the specific yield and coefficient of variation contour lines are given in Part 2 (Figures P9 through P13).

It was stated earlier that criteria of suitability for maximum water gain and minimum time evaluation were not necessarily the same. The selected criteria in this report are indeed different. It was tacitly implied then that the criteria might not be compatible. The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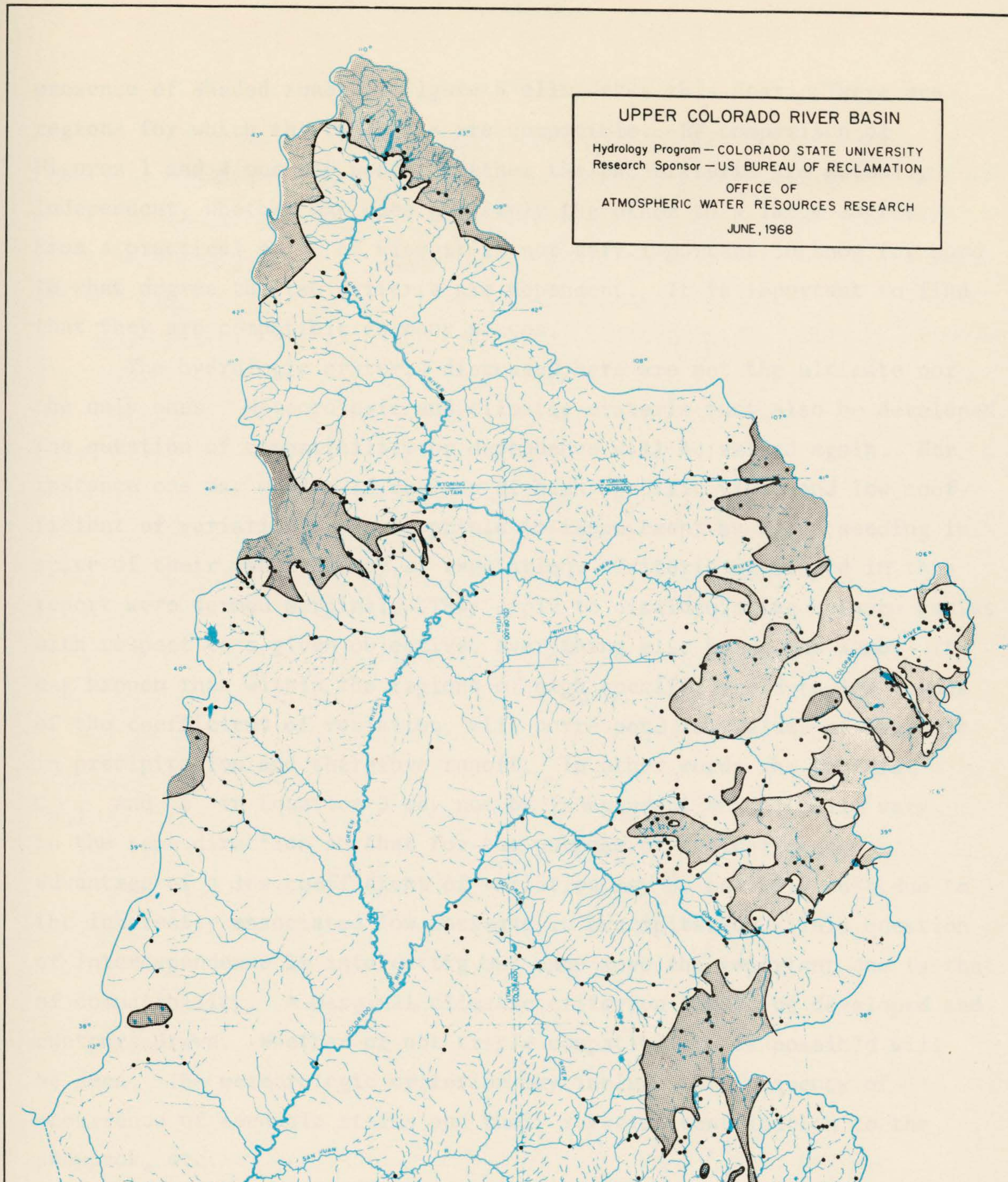
ATMOSPHERIC WATER RESOURCES RESEARCH
JUNE, 1968
LEGEND
REGIONS WITH ANNUAL SPECIFIC YIELD GREATER THAN 10"
GAGING STATION
25 0 25 50
SCALE
GREEN RIVER
COLORADO RIVER
SAN JUAN
WYOMING UTAH
WYOMING COLORADO
UTAH ARIZONA
COLORADO NEW MEXICO
YAMPA RIVER
WHITE
GUNNISON

Fig. 4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REGIONS WITH ANNUAL SPECIFIC YIELD GREATER THAN 10" AND ANNUAL COEFFICIENT OF VARIATION LESS THAN 30 %
GAGING STATION
25 0 25 50
SCALE

Fig. 5

presence of shaded zones in Figure 5 eliminates this fear. There are regions for which the two goals are compatible. By comparison of Figures 1 and 4 one may wonder whether the two criteria are actually independent, whether one does not imply the other to a large degree. From a practical point of view it is not very important to know for sure to what degree the two criteria are dependent. It is important to find that they are compatible in many places.

The hydrologic criteria discussed here are not the ultimate nor the only ones. Meteorologic and climatic criteria must also be developed. The question of compatibility or dependence will be raised again. For instance one may wonder if regions of high specific yield and low coefficient of variation are susceptible to improvement by cloud seeding in spite of their own tendency at regulation. Criteria developed in this report were termed marginal. They apply to distinguishing between basins with respect to a given objective, everything else being the same. It may happen that within the regions of high specific yield to low values of the coefficient of variation, will correspond low values of increase in precipitation and therefore runoff. In other words the factors $C_{v,T}$ and κ in Equation 3 may not be independent but actually vary in the same direction so that for the purpose of evaluation the advantage of a low coefficient of variation may be entirely lost due to the inherently associated low increase in precipitation. This question of interdependence is interesting but once more the important one is that of compatibility. A marginal climatic criterion should be developed and contours drawn. Whether or not triple compatibility is possible will be seen. The meteorologic criterion may include the frequency of occurrence of seedable storms and their relative contribution to the snowpack, etc.

Figure P14 illustrates a measure of flow variability with seasons. It shows contour lines of ratio of spring runoff (April through July, a measure of the accumulated snowpack) to the remainder of the water year. If flow were uniformly distributed throughout the year this ratio should have the constant value of 0.5. On the contrary, this quantity is usually large and can be as high as 30. In other words, most of the annual water flow comes from the melt of the high elevation snowpacks during the spring and early summer months.

G. PREDICTION OF SPECIFIC YIELD

For reasons explained in a previous section, a tentative answer to the question of "what makes one basin more suitable than another" is: "a naturally high specific yield." However, for many basins which are ungaged one cannot determine the value of the specific yield from past records. Therefore an alternative must be devised to remedy this absence of data. Such an alternative was developed and was described in an earlier report (15). The present section describes to a large degree an extension of this former procedure. There are a few major differences:

(1) Equations were developed to predict both the specific yield and the yield, and

(2) The equations were developed for different subregions within the Upper Colorado River Basin.

From a physical point of view it should make no difference whether an equation estimates specific yield directly or estimates yield from which the specific yield is then deduced by dividing by the basin area. However this is not true when approximations to the physical situation are derived by statistical techniques, because most statistical techniques proceed from a priori postulated mathematical models of the physical reality. The hypothesis may then be tested and accepted or rejected. For example let us assume that the "true" relation between yield and area of a basin is of the form:

$$Q = A^n \quad (4)$$

and consequently

$$q = \frac{Q}{A} = A^{n-1} \quad . \quad (5)$$

Suppose now that one chooses to approximate the true relation, which is usually unknown, by a simple linear regression model of the form:

$$Q = A \quad (6) \quad , \text{or} \quad q = A \quad (7)$$

The coefficient of determination (the square of the coefficient of correlation) for Equations 6 and 7 will be different depending on the actual value of n. If the value of n is close to 1 then the coefficient of determination for Equation 6 will be very high, that for Equation 7 will be low, and vice-versa if the value of n is close to 2. Because the value of n is unknown, then one has to try both Equations 6 and 7 and, based on the calculated value of the coefficient of determination, one then decides which of the two equations is a better estimator of the physical reality.

The second main difference lies in the regions that were studied. The stations that were utilized for the development of the correlations were located in the White River drainage basin and the Grand Mesa area. Altogether 63 basins were studied. Figure 6 shows the areas for which prediction equations were developed.

Fundamentally linear multiple regression analysis was carried for yield or its logarithm (base 10) versus various physiographic predictor variables in the form of either

$$Q = \text{constant} + \sum_i a_i x_i$$

or

$$\log Q = \text{constant} + \sum_i a_i \log x_i \, .$$

The same procedure was carried for specific yield, but the coefficients of determination were so much smaller that the results are not reported. Of course the prediction equation for specific yield is obtained from the prediction equation for Q and by dividing by the basin area, A.

A variety of predictor variables were used. Only those that turned out to be significant are defined in Table 7. The results are summarized in Tables 8 through 12. Table 12 shows the improvement over the results of references 15 or 16, in which coefficients of determination varied between 50 and 77%. The prediction equation of Table 12 corresponds to the region shown in Figure 7.

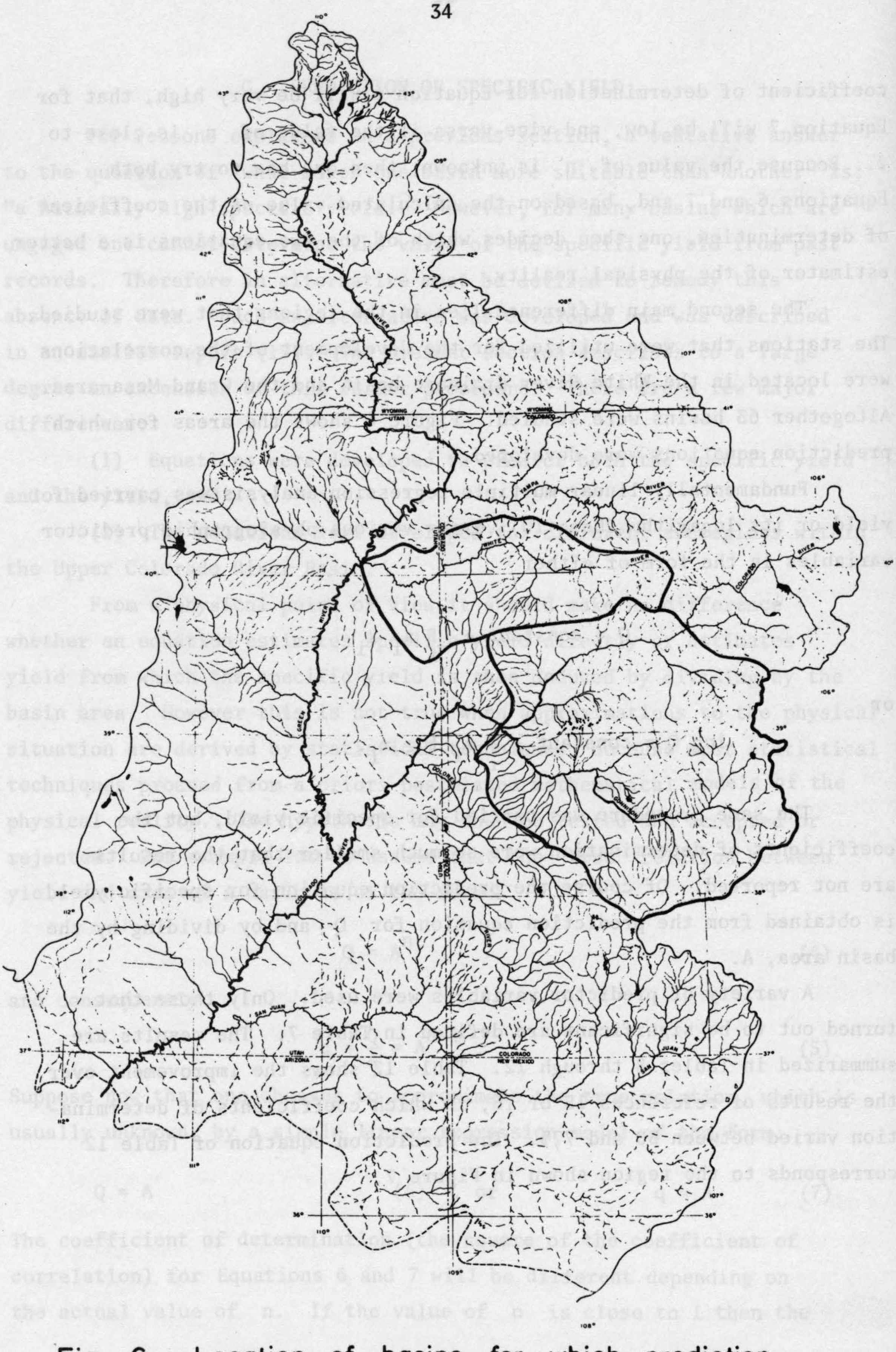

Fig. 6 Location of basins for which prediction equations of yield were derived.

TABLE 7

VARIABLES USED IN THE REGRESSION ANALYSIS FOR PREDICTION OF WATER YIELD

A = Area of the basin (a measure of "size effect") in square miles

B = Boundary length (not used as such but in the combination $\sqrt{A}/B$, a measure of "shape effect")

L_{9000} = Length of boundary above 9000 feet (a "moisture catching effect") in miles

$L_p/\sqrt{A}$ = L_p is the projected length of orographic barrier with elevations exceeding 80% of the elevation difference between the largest elevation and the lowest elevation (a measure of the "orographic zone effect"). Points c and d are referred to as "cut-off points."

H_μ = Mean basin elevation (obtained from hypsometric curves on log probability paper, an elevation i.e. "temperature effect") in feet.

$H_{0.05}$ = Heights above which lies only 5% of the total basin area in feet.

$H_{0.10}$, $H_{0.25}$, $H_{0.75}$, $H_{0.90}$, $H_{0.95}$ "Similar definitions (a "distribution of area vs. elevation effect").

A_{9000} = % of area of basin above 9000 feet, a number between 0 and 100.

A_{9500} = % of area of basin above 9500 feet.

L_s = Main stream length in miles

Lat. = Latitude minus 36^o.

L = Length of basin in miles, longest horizontal distance from the major drainage divide to the stream gage at the basin mouth.

$\Delta H_1/L$ = $(H_{.05} - H_{.95})$/length of basin (ft/mi).

O_2 = Orientation of basin numerically equal to 1, 2, 3, 4 if orientation is respectively N, E, W, S.

Q = Yield in cfs.

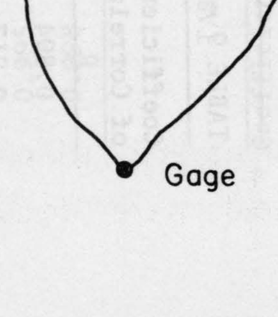

TABLE 8 - PREDICTION EQUATION PARAMETERS FOR THE GUNNISON RIVER REGION

Coefficient of Correlation R	Coefficient of Determination R^2	Estimated Variable (yield)	Constant	Coefficients of Predictor Variables: A	Coefficients of Predictor Variables: H_μ	Confidence Limits for R at 95% Level	
0.956	0.91	Q	10.2	0.79	-		
0.960	0.92	Q	-120	0.79	0.013	0.92	0.98
				logA	$\log A_{10000}$		
0.934	0.87	logQ	0.016	0.97	-		
0.961	0.92	logQ	-0.573	0.89	0.29	0.92	0.98

TABLE 9 - PREDICTION EQUATION PARAMETERS FOR THE COLORADO RIVER REGION ABOVE THE CONFLUENCE OF THE GUNNISON

Coefficient of Correlation R	Coefficient of Determination R^2	Estimated Variable (yield)	Constant	Coefficients of Predictor Variables					Confidence Limits for R at 95% Level	
				$\log L_{9000}$	$\log \frac{L_p}{\sqrt{A}}$	logA	$\log H_{0.25}$	$\log A_{9500}$		
0.894	0.80	logQ	-0.56	1.54	-	-	-	-		
0.917	0.84	logQ	-0.54	1.56	0.45	-	-	-		
0.930	0.87	logQ	-0.44	1.12	0.51	0.32	-	-		
0.943	0.89	logQ	-11.1	0.55	0.24	0.59	2.73	-		
0.951	0.905	logQ	-20.3	0.57	0.22	0.52	5.23	-0.27	0.89	0.98

TABLE 10 - PREDICTION EQUATION PARAMETERS FOR THE WHITE RIVER REGION

Coefficient of Correlation R	Coefficient of Determination R^2	Estimated Variable (yield)	Constant	Coefficients of Predictor Variables		Confidence Limits for R at 95% Level	
				A	L_{9000}		
0.99	0.98	Q	-15.9	1.42			
0.998	0.997	Q	-29.1	0.94	1.74	0.99	1
				$\log L_{9000}$	$\log \frac{L_p}{\sqrt{A}}$		
0.995	0.99	logQ	-1.05	1.91	-		
0.998	0.996	logQ	-0.81	1.80	0.79	0.99	1

TABLE 11 - PREDICTION EQUATION PARAMETERS FOR THE GUNNISON-COLORADO-WHITE RIVERS COMBINED REGION

Coefficient of Correlation R	Coefficient of Determination R^2	Estimated Variable (yield)	Constant	Coefficients of Predictor Variables: $\log L_{9000}$	$\log \frac{\sqrt{A}}{B}$	$\log L_s$	Confidence Limits for R at 95% level	
0.936	0.876	logQ	-0.75	1.67	-	-		
0.948	0.899	logQ	0.16	1.77	1.54	-		
0.954	0.910	logQ	0.35	1.46	1.84	0.42	0.92	0.97

TABLE 12 - PREDICTION EQUATION PARAMETERS FOR THE REGION SHOWN IN FIGURE 7

Coefficient of Correlation R	Coefficient of Determination R^2	Estimated Variable (yield)	Constant	Coefficients of Predictor Variables A	L_{9000}	ϕ_2	Lat	$\frac{\Delta H_1}{L}$	Confidence Limits for R at 95% Level
0.784	0.614	Q	8.36	0.84	-	-	-	-	
0.861	0.741	Q	-22.7	0.52	1.81	-	-	-	
0.879	0.773	Q	-65.7	0.50	2.08	13.1	-	-	
0.889	0.79	Q	-96	0.46	2.45	12.4	4.97	-	
0.900	0.81	Q	-154	0.59	2.59	10	7.49	0.18	0.84 0.94

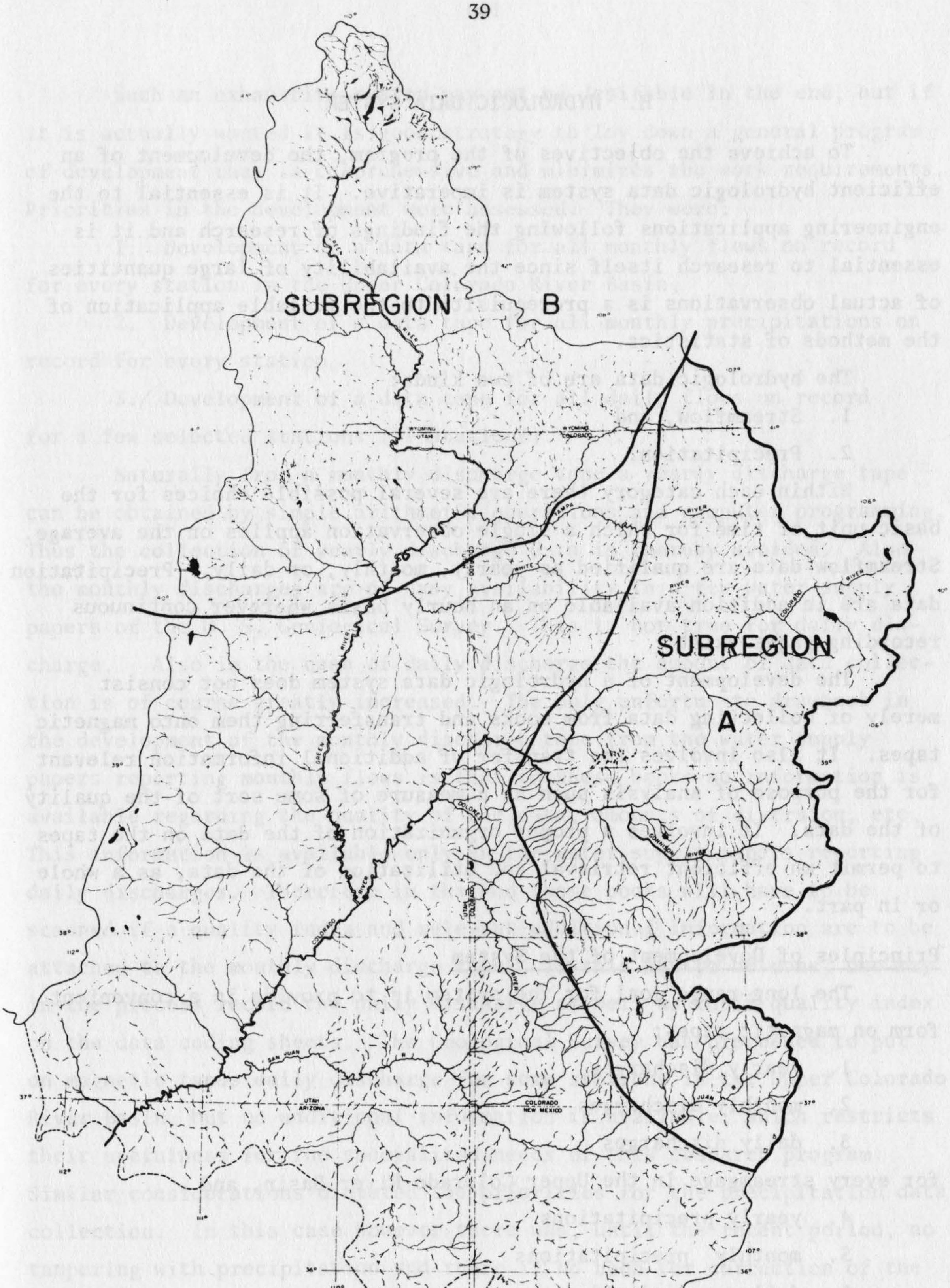

Fig. 7 Location of subregions for which prediction equations of yield were rederived.

H. HYDROLOGIC DATA SYSTEM

To achieve the objectives of the program, the development of an efficient hydrologic data system is imperative. It is essential to the engineering applications following the findings of research and it is essential to research itself since the availability of large quantities of actual observations is a prerequisite to the reliable application of the methods of statistics.

The hydrologic data are of two kinds:

1. Streamflow, and
2. Precipitation.

Within each category there are several possible choices for the basic unit of time for which a single observation applies on the average. Streamflow data are qualified as yearly, monthly, or daily. Precipitation data are in addition available on an hourly basis wherever continuous recording gages exist.

The development of a hydrologic data system does not consist merely of collecting data from books and transferring them onto magnetic tapes. It also involves the transfer of additional information relevant for the purpose of analysis such as a measure of some sort of the quality of the data. It involves a proper organization of the data on the tapes to permit an efficient retrieval and utilization of the data, as a whole or in part.

<u>Principles of Development of the System</u>

The long-range goal for the system is to provide in a convenient form on magnetic tapes:

1. yearly discharges
2. monthly discharges
3. daily discharges

for every streamgage in the Upper Colorado River Basin, and

4. yearly precipitations
5. monthly precipitations
6. daily precipitations
7. hourly precipitations,

for every precipitation gage in the same region.

Such an exhaustive system may not be desirable in the end, but if it is actually wanted it is good strategy to lay down a general program of development that is comprehensive and minimizes the work requirements. Priorities in the development were assessed. They were:

1. Development of a data tape for all monthly flows on record for every station in the Upper Colorado River Basin,

2. Development of a data tape for all monthly precipitations on record for every station,

3. Development of a data tape for all daily flows on record for a few selected stations (31 stations).

Naturally from a monthly discharge tape a yearly discharge tape can be obtained by simple arithmetic operations and computer programming. Thus the collection of yearly discharge data is thereby avoided. Also the monthly discharges are of easy availability in a few water supply papers of the U. S. Geological Survey. This is not true for daily discharge. Also in the case of daily discharge the amount of data collection is of course greatly increased. The only unfortunate drawback in the development of the monthly discharge tape from the water supply papers reporting monthly flows is that in these books no information is available regarding the quality of the data, amounts of diversion, etc. This information is available only in the water supply papers reporting daily discharges. Therefore in the end these books will have to be scanned if a quality index and relevant additional information are to be attached to the monthly discharge tape. If this has to be done, one may in the process record the daily discharge as well as their quality index on the data coding sheets. The Geological Survey has proceeded to put on magnetic tapes daily discharge for some stations in the Upper Colorado River Basin, but no additional information is available, which restricts their usefulness for the specialized needs of this research program. Similar considerations dictated the priorities for the precipitation data collection. In this case however there was, until the recent period, no tampering with precipitation and there is no need for correction of the data due to man's activities. A daily precipitation tape in this context appears of relatively little value. For refined analyses an hourly precipitation tape, including storm durations, would be more meaningful and its development would require little more effort.

In summary the corner stones of the development of the complete system are the development of:

1. A monthly discharge tape for all stations, but without additional information pertaining to accuracy of data or extent of man's activities through diversion, reservoir storage, etc. (i.e. without the so-called "quality indices"),

2. A monthly precipitation tape for all stations,

3. A daily discharge tape for all stations and with the quality indices,

4. A new monthly discharge tape obtained from the daily flows tape and therefore with quality indices for all stations, and

5. An hourly precipitation tape for all stations.

Present Stage of Development

A monthly discharge tape for all stations in the Upper Colorado River Basin is now available. A check of the proper organization of the tape and of the correctness of the information was carried by selective printing of monthly flows for several stations located throughout the tape. Table 4 of Part 3 illustrates a typical print-out of monthly flow records for a given station from the tape. Figures 1, 4, 5, and P1 through P14 in Part 2 were drawn on the basis of statistics computed from the monthly flow tape. Tables 5 through 11 in Part 3 illustrate the use of the system to sort in the streamgages and rank them with respect to coefficient of variation, specific yield, and ratio of 4 months (April-July) runoff, to the remainder of the water year.

It appeared necessary in the development of the system to have an immediate reference to a list of all stations in the Upper Colorado River Basin. A master chart for all streamgages in the region has been developed. This list is available in Part 3.

For the purpose of analysis it appeared useful to develop a new numbering system for the streamgages and precipitation gages in the region. This new numbering system is described in the next section.

Stations' New Numbering System

The basic assumption behind the numbering philosophy is that most subregions under study will correspond to a natural drainage area. The numbering system is such that all stations within a drainage area and only them have a number intermediate between two limiting numbers that characterize the downstream and upstream reach of the drainage area. As stations on the tape are ordered sequentially, data pertaining to a given drainage area are located on a contiguous section of the tape which guarantees the fastest accessibility to the data.

For many regions in the Upper Colorado River Basin it will be essential to characterize accurately the relation between precipitation and runoff. As the numbering system of the Geological Survey and that of the Weather Bureau are unrelated, it is impossible to bring together systematically a streamgage and a precipitation gage pertaining to the same drainage area. The new numbering system for precipitation gages is geared specifically to remedy this inconvenience. The new number of the precipitation gage is that of the streamgage that is nearest within the same drainage area.

The numbers for the streamgages were assigned in an upstream order along the main stem of the Colorado River. The compact point, which is at the lower extremity of the basin, was assigned the number 1,000,000. Grant River Ditch at La Poudre Pass, which is at the upper extremity of the basin was assigned the number 1,980,000. All other station numbers fall between these two numbers. All stations on a tributary whose confluence with the main river lies between two main river stations, e.g., numbered N and N+n, have numbers between N and N+n. This numbering procedure was applied to all tributaries of all ranks. The general procedure is illustrated in Figure 8. Working maps of the Upper Colorado River Basin displaying the station number are given in Part 2, (maps 1 through 5). In Part 3, the correspondence between the G. S. number and the CSU number is given in table form. The format of the tape is also given there.

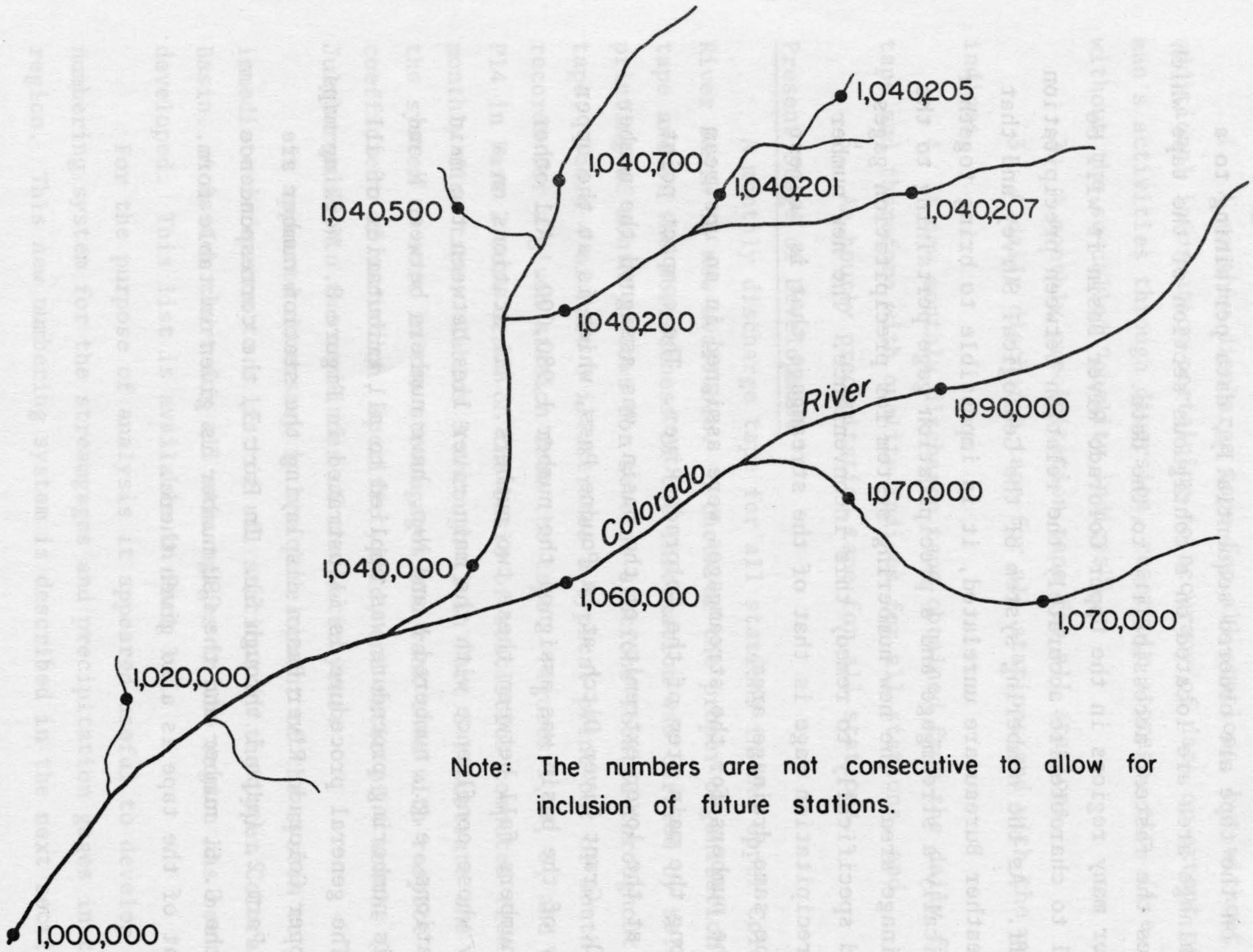

Fig. 8 Illustration of Numbering System

I. RUNOFF MEASUREMENT ERRORS

The purpose of the study was to analyze the errors that may be incurred in discharge determinations made on mountain streams. The possible sources of error have been considered and a classification of these sources has been prepared (18), (19). A mathematical error model for a single discharge measurement was developed (18), (20). Based on a limited sample of data it appears unlikely that the relative error will exceed 4% for more than 5% of the time. For an annual estimate of discharge the relative error will remain within 3% in most instances. No studies have yet been made to decide whether this magnitude of error may lead to wrong statistical inferences and, if so, with which frequency. Because the magnitude of the error seemed small, the study was not given priority. However, an annual 3% error may not be altogether negligible, relative to a 15-year mean increase of the order of 5% (re: Table 5).

J. INCOMPLETE RESEARCH EFFORTS

Several efforts have not reached fruition in the sense that their practical value is yet to be established. A thorough discussion of these efforts would seem premature. They are therefore discussed only briefly here.

There are drawbacks in using annual runoff as the basic variable for detection of weather modification attainments. Inevitably the choice of that variable reduces the sample size, for the period of seeding, to less than twenty. One of the reasons for the choice of the annual runoff is that runoffs from year to year can be regarded as independent random variables from the same (and assumed stationary) distribution, and therefore most statistical tests are applicable. In order to increase the sample size, and thereby reduce the actual duration of an experiment poised to establish the statistical significance of cloud seeding, consideration should be given to monthly or daily runoff. In this case the assumption of independence is incorrect. Prior to designing a statistical test it becomes necessary to investigate the stochastic structure of monthly or daily runoff. But the stochastic models also involve assumptions, and it is not apparent for runoff which assumptions are physically pertinent. On the other hand, realistic assumptions can be made regarding the stochastic structure of precipitation. For this reason it was decided to develop a stochastic model for precipitation first and then deduce from it a stochastic model for runoff.

The model is based on the reasonable assumption that the occurrence of two or more separate storms within a short interval of time is unlikely, and even more unlikely if the time interval is extremely small. Based on this assumption the probability laws governing the frequency of storms within a period of time and the total precipitation amount for a storm were derived. A few results are now outlined.

Symbolically if one denotes by

$$P(E_k^{\,t,t+\Delta t}/E_j^{\,o,t})$$

the probability of occurrence of k ends of separate storms in the time interval (t, t+Δt), given that j storms ended in the time interval (o,t), the above mentioned assumptions take the form:

$$P(E_1^{t,t+\Delta t}/E_j^{o,t}) = \lambda_j \Delta t \tag{8}$$

and

$$P(E_i^{t,t+\Delta t}/E_j^{o,t}) = 0 \quad \text{for } i > 1. \tag{9}$$

If one assumes that the probability in Equation 8 is independent of time and of antecedent conditions, that is does not depend upon whether the previous days or months were wet or dry, one obtains the result:

$$P(E_\nu^{o,t}) = e^{-\lambda t} \frac{\lambda^\nu}{\nu!} t^\nu ,$$

which says that the probability of occurrence of exactly ν complete storms in the interval of time (o,t) equals the explicit expression on the right-hand side. The above result has been obtained for various stochastic processes, but only one application of this result to precipitation is known to us.

If λ does not depend upon antecedent conditions but depends on time (which is a fact, as there are seasons in the year) an equation is obtained of the form

$$P(E_\nu^{o,t}) = e^{-\Lambda(t)} \frac{[\Lambda(t)]^\nu}{\nu!}$$

where $\Lambda(t) = \int_o^t \lambda(t)\, dt$.

Even in the case of dependence of the probability of occurrence of one storm in a short interval of time upon antecedent conditions, an expression for $P(E_\nu^{o,t})$ was obtained. These results are new and the corresponding stochastic models correspond more closely to reality.

Even though the assumptions of the model appear realistic, the model must be checked. Besides, parameters of the distribution such as $\lambda(t)$ must be evaluated on the basis of actual data. The physical meaning of parameter $\lambda(t)$ is simple: it is the average number of storms during a season of the year.

For this reason precipitation data over 54 years (1914-1967) were collected for a station (Austin, Texas). Based on these data a comparison could be made between the theory and the observation. A comparison is illustrated graphically in Figure 9. The rigorous mathematical treatment of the theory is presented in reference 21.

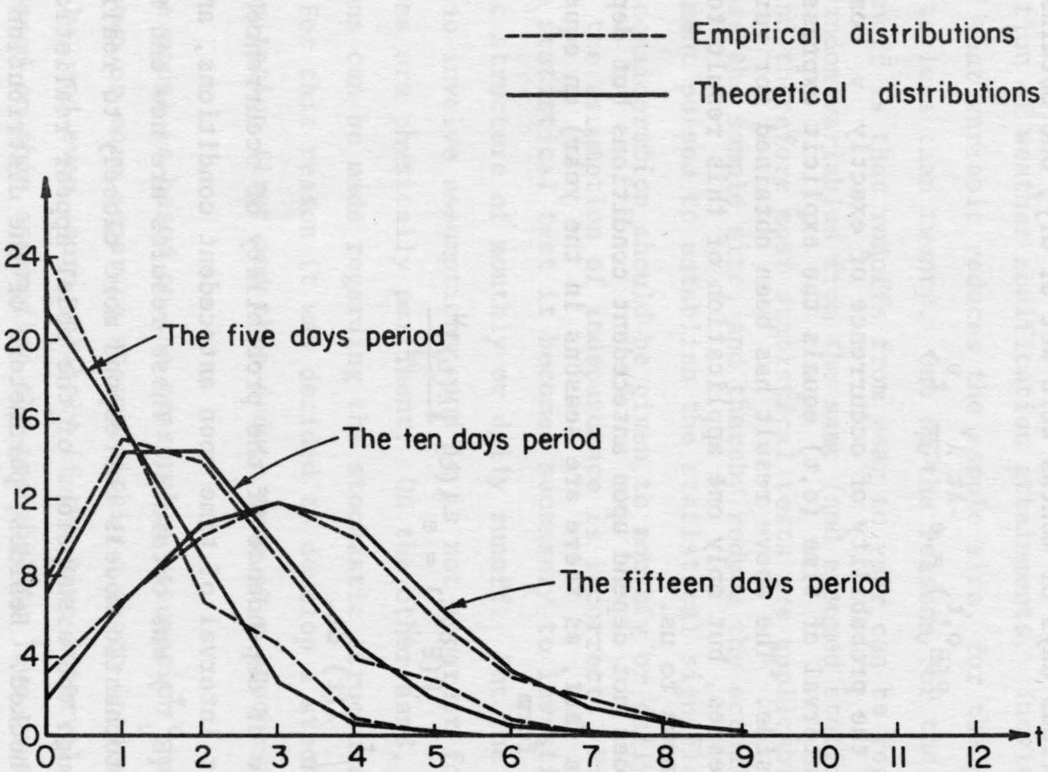

Fig. 9 Comparison of theoretical and empirical distributions of the number of stormy days within a given period.

Once the model is proven to fit reality satisfactorily, it can be used to develop a statistical test based on precipitation data before and after seeding operations. But it can also be used to obtain a stochastic model of runoff for a particular basin using the actual hydrograph of the basin. The resulting model for runoff can then serve as a basis for a statistical test.

Another area of research was an effort of developing a statistical relation between precipitation amounts and meteorological parameters. The precipitation amounts will depend on meteorological parameters beyond modification, and on others that are most directly affected by cloud seeding. From the correlation one would obtain a statistical meteorologic criterion of suitability of a basin to weather modification. However up to now the attempt has not been very successful.

K. CONCLUSIONS AND RECOMMENDATIONS

Statistical tests were developed to detect significance in attainment of increased runoff. One test, the target control conditional Student's t-test, seems particularly valuable. It appears rather insensitive to even large deviations from normality. It is a "robust" test. Though its power was not theoretically calculated, it was verified using actual data.

It seems that more attention should be given to proper choice of the variable to be tested in order to maintain proper balance with further refinements in the tests. Also attention should refocus from the early insistence in proving significance to the problem of estimation of the increase and its confidence limits.

Simple criteria of suitability of basins to weather modification were developed and applied to the Upper Colorado River Basin. The application points to three main regions within the basin where optimal conditions obtain for both increased water resources and evaluation purposes. These areas center around Vail (upper portions and tributaries of the Williams and Blue Rivers), around Marble (upper Crystal River), Roaring Fork and tributaries of the Gunnison River), and around Red Mountain.

The location of these areas should be further supported by repeating the procedures on streamflow data, thoroughly corrected back to the natural values that would have prevailed without man's intervention. They should also be supported by studies involving more refined criteria.

ACKNOWLEDGMENTS

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PART 1

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APPENDIX A -- PERSONNEL

From July 1, 1966 to August 1967, the research described in this report was carried out under the direction of Dr. V. Yevjevich, Professor-In-Charge of the Hydrology Program and Principal Investigator. From August 1967 to the termination date of the contract, Dr. H. J. Morel-Seytoux, Associate Professor of Civil Engineering, was principal investigator.

Much of the work done on devising statistical tests of evaluation of weather modification attainments was contributed by Dr. R. D. Markovic, former graduate student at Colorado State University. Another former graduate student, Dr. W. T. Dickinson, is responsible for the study of runoff measurement errors. The study of statistical prediction equations for yield based on physiography was initiated by Mr. R. W. Julian in his Master's Thesis and extended by Mr. Viboon Nimmannit, presently a graduate student at Colorado State University. The development of the hydrologic data system was the responsibility of another graduate student, Mr. R. L. Brustkern. Dr. P. Todorovic developed the mathematical model of precipitation phenomena.

APPENDIX B

LIST OF DATA TO TEST VALUE OF VARIOUS STATISTICAL TESTS

TABLE 13

LIST OF DATA USED TO TEST VALUE OF VARIOUS STATISTICAL TESTS

RUN NUMBER = 1

TEST OF SIGNIFICANCE ON SEASON RUNOFF OF SOUTH FORK,SAN JOAQUIN

CONTROL IS MERCED RIVER

LIST OF DATA AS READ

11.0641922	31.00	22.00	37.00	55.90	65.90	87.70	233.00	1090.00	2070.00	1070.00	317.00	102.00
11.0621922	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
11.0631922	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
11.0641923	30.50	53.50	78.10	72.70	62.80	87.60	191.00	933.00	887.00	737.00	201.00	111.00
11.0621923	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
11.0631923	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
11.0641924	56.60	25.70	14.50	10.60	18.30	20.50	146.00	556.00	152.00	93.20	49.20	28.10
11.0621924	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
11.0631924	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
11.0641925	16.20	25.30	29.00	30.80	68.80	124.00	190.00	776.00	292.00	11.40	.20	.08
11.0621925	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
11.0631925	0.	0.	0.	0.	0.	0.	3960.00	12700.00	53400.00	40600.00	18000.00	3210.00
11.0641926	.26	.30	.19	.35	2.39	2.66	56.60	76.00	1.51	1.10	1.02	1.90
11.0621926	0.	360.00	488.00	562.00	430.00	1269.00	6134.00	30097.00	35029.00	33002.00	7448.00	37.00
11.0631926	2360.00	1820.00	2090.00	1050.00	2480.00	6010.00	30500.00	42400.00	33300.00	13400.00	29400.00	9100.00
11.0641927	9.73	1.77	1.90	1.97	12.20	20.20	94.00	601.00	935.00	94.00	10.00	6.90
11.0621927	79.00	637.00	675.00	665.00	667.00	705.00	894.00	898.00	41105.00	64579.00	49046.00	29498.00
11.0631927	502.00	2740.00	4690.00	3500.00	6220.00	7750.00	12600.00	22300.00	3640.00	30900.00	28000.00	22700.00
11.0641928	6.34	12.90	9.63	1.96	1.78	1.16	.20	.36	138.00	5.45	.44	.74
11.0621928	18702.00	0.	551.00	547.00	551.00	569.00	1369.00	50904.00	64753.00	52374.00	25382.00	521.00
11.0631928	12900.00	25000.00	2290.00	2660.00	2690.00	7070.00	13600.00	19500.00	23300.00	23500.00	30400.00	25500.00
11.0641929	2.46	2.29	2.26	2.13	1.89	1.88	.26	.33	2.57	2.88	2.85	2.91
11.0621929	589.00	524.00	529.00	552.00	553.00	554.00	678.00	25720.00	63532.00	59941.00	36344.00	7851.00
11.0631929	861.00	994.00	1140.00	1120.00	1300.00	4080.00	7380.00	19700.00	6840.00	23400.00	30400.00	30900.00
11.0641930	2.71	2.10	1.49	1.30	2.01	1.96	1.50	1.51	2.36	3.07	2.85	2.90
11.0621930	496.00	542.00	533.00	518.00	509.00	503.00	594.00	19850.00	64002.00	54564.00	29588.00	1723.00
11.0631930	8360.00	453.00	799.00	1250.00	1940.00	6060.00	15400.00	10000.00	13000.00	24800.00	29400.00	29200.00
11.0641931	2.56	1.49	1.34	1.55	1.55	2.03	1.15	.96	1.54	1.93	2.19	1.28
11.0621931	519.00	538.00	529.00	568.00	590.00	550.00	799.00	11491.00	788.00	629.00	593.00	599.00
11.0631931	2600.00	988.00	545.00	744.00	1010.00	2180.00	10500.00	25400.00	25300.00	5540.00	5770.00	3060.00
11.0641932	1.30	1.19	1.00	.80	.90	1.36	1.57	2.56	601.00	600.00	11.70	2.85
11.0621932	553.00	557.00	513.00	604.00	534.00	575.00	580.00	6530.00	62681.00	65052.00	54729.00	31403.00
11.0631932	1590.00	1260.00	2800.00	4700.00	5900.00	9200.00	16000.00	46000.00	7300.00	23000.00	22300.00	25500.00
11.0641933	2.37	3.28	1.58	.70	.70	.80	.47	.16	.51	1.42	1.00	1.05
11.0621933	589.00	572.00	505.00	552.00	551.00	579.00	586.00	4060.00	63532.00	64060.00	50931.00	22449.00
11.0631933	31700.00	815.00	812.00	1380.00	2150.00	3760.00	11500.00	17800.00	18400.00	31700.00	19200.00	29800.00
11.0641934	.95	1.05	.80	.21	.30	.27	13.80	.12	.42	.33	.82	.63
11.0621934	599.00	81.00	133.00	127.00	134.00	376.00	11643.00	42646.00	17081.00	583.00	518.00	120.00
11.0631934	22500.00	1340.00	2060.00	2140.00	2430.00	8180.00	11700.00	2560.00	41100.00	24700.00	4890.00	2810.00
11.0641935	.81	.83	.74	.26	.33	.35	.31	.06	241.00	99.70	1.48	1.07
11.0621935	89.00	97.00	97.00	149.00	136.00	314.00	738.00	10872.00	65255.00	64271.00	53915.00	31327.00
11.0631935	1280.00	1920.00	1980.00	3610.00	4300.00	5750.00	21140.00	37330.00	30540.00	28630.00	21010.00	27410.00
11.0641936	1.00	1.13	.71	.40	.57	.68	.27	.11	174.00	237.00	1.71	1.53
11.0621936	1059.00	96.00	98.00	109.00	212.00	5308.00	6142.00	39599.00	64627.00	64233.00	52518.00	24233.00
11.0631936	31760.00	2930.00	1450.00	2580.00	5230.00	5590.00	29100.00	36880.00	45390.00	32150.00	24970.00	30560.00

TABLE 13 - Continued:

11.0641937	1.21	1.25	.70	.82	1.30	1.25	.81	.14	877.00	224.00	1.27	.53
11.0621937	671.00	69.00	154.00	134.00	285.00	307.00	631.00	64464.00	64339.00	64098.00	51700.00	52166.00
11.0631937	25410.00	2280.00	2070.00	3470.00	7100.00	7330.00	17660.00	19910.00	40270.00	32010.00	21510.00	1380.00
11.0641938	.80	.32	1.79	.66	1.92	1.52	300.00	171.00	1714.00	1218.00	219.00	1.55
11.0621938	52897.00	9501.00	162.00	163.00	205.00	214.00	863.00	20654.00	56201.00	64377.00	64271.00	59321.00
11.0631938	87.00	44340.00	17340.00	3020.00	6010.00	9520.00	5470.00	35250.00	89.00	22610.00	22240.00	14810.00
11.0641939	1.16	1.47	.91	1.31	1.06	1.71	.14	.20	1.12	1.26	.98	1.40
11.0621939	92400.00	61800.00	31300.00	178.00	154.00	287.00	8320.00	49500.00	63900.00	62100.00	61800.00	61400.00
11.0631939	2850.00	4500.00	32750.00	33540.00	3340.00	6510.00	17120.00	52.00	14870.00	15410.00	10080.00	3970.00
11.0641940	1.21	1.18	.47	1.94	.59	.93	3.53	.13	549.00	49.30	.82	1.08
11.0621940	92000.00	59400.00	14100.00	219.00	222.00	405.00	806.00	45300.00	64700.00	63500.00	42700.00	12200.00
11.0631940	3710.00	3020.00	46430.00	18830.00	4960.00	11000.00	22010.00	36140.00	39250.00	25220.00	27930.00	32790.00
11.0641941	.90	6.57	1.40	1.14	1.27	18.90	3.59	179.00	1113.00	690.00	1.66	.59
11.0621941	409.00	128.00	264.00	198.00	208.00	271.00	730.00	43600.00	61100.00	64400.00	62900.00	40500.00
11.0631941	12900.00	1470.00	3230.00	4940.00	5410.00	6920.00	11580.00	10580.00	28490.00	51460.00	29270.00	26700.00
11.0641942	.30	.24	1.26	1.99	1.60	1.81	2.25	108.00	.67	464.00	1.49	.55
11.0621942	19100.00	4180.00	298.00	218.00	168.00	315.00	390.00	1280.00	60800.00	64300.00	59400.00	35600.00
11.0631942	22780.00	17210.00	9520.00	6200.00	4390.00	6700.00	16920.00	32740.00	41900.00	38490.00	22170.00	26790.00
11.0641943	.25	1.52	.33	.20	.10	.35	1.40	.50	.77	1.85	1.92	.71
11.0621943	4420.00	135.00	155.00	269.00	233.00	426.00	1110.00	22900.00	43700.00	63700.00	52700.00	29500.00
11.0631943	32120.00	5910.00	2150.00	3800.00	4490.00	7990.00	21180.00	40110.00	39080.00	28560.00	23490.00	26030.00
11.0641944	.57	1.76	.38	.03	.03	.10	.21	.07	.27	1.05	.66	.04
11.0621944	4150.00	118.00	692.00	743.00	633.00	907.00	728.00	20800.00	59100.00	63400.00	44200.00	18800.00
11.0631944	26510.00	5110.00	756.00	1830.00	2830.00	5430.00	8720.00	25470.00	17080.00	33070.00	26480.00	27720.00
11.0641945	.48	.09	.05	0.	.15	.04	.14	.01	.60	139.00	2.01	.52
11.0621945	654.00	197.00	214.00	184.00	228.00	324.00	3080.00	2340.00	54100.00	64200.00	52600.00	44800.00
11.0631945	18670.00	3940.00	3690.00	2850.00	6030.00	5620.00	17220.00	54430.00	41760.00	45240.00	31420.00	13330.00
11.0641946	.70	52.90	9.14	0.	.01	.14	.07	.03	1.05	10.80	.73	.81
11.0621946	58200.00	63800.00	5620.00	242.00	276.00	451.00	11600.00	36400.00	64600.00	63600.00	50200.00	24400.00
11.0631946	0.	175.00	65420.00	11550.00	4010.00	8760.00	19230.00	50950.00	43870.00	35240.00	23490.00	28570.00
11.0641947	2.44	2.42	.18	0.	.06	.10	.47	1.11	2.36	3.13	3.70	3.46
11.0621947	18400.00	2860.00	291.00	231.00	252.00	339.00	965.00	41900.00	63500.00	53400.00	28000.00	2290.00
11.0631947	10530.00	20060.00	8680.00	3760.00	3990.00	6980.00	17640.00	32750.00	18160.00	21460.00	29960.00	27690.00
11.0641948	2.87	.01	0.	.01	.01	.04	.23	1.15	1.98	2.89	3.61	3.90
11.0621948	761.00	208.00	190.00	175.00	189.00	266.00	429.00	22700.00	60700.00	60600.00	35200.00	19000.00
11.0631948	4760.00	3130.00	1740.00	1650.00	1980.00	2050.00	9820.00	26210.00	32940.00	22920.00	29260.00	16810.00
11.0641949	3.37	3.35	1.74	.48	.10	.11	.40	1.51	2.84	3.72	3.97	4.08
11.0621949	982.00	300.00	191.00	191.00	208.00	243.00	2820.00	22700.00	63500.00	57000.00	35300.00	37100.00
11.0631949	18150.00	1390.00	1140.00	1220.00	1450.00	3030.00	16610.00	33860.00	20550.00	20630.00	26780.00	89.00
11.0641950	4.03	21.00	4.45	.03	.08	.13	.56	1.41	2.78	3.57	4.14	3.79
11.0621950	29400.00	95.00	207.00	239.00	307.00	395.00	5410.00	37000.00	59200.00	60300.00	34300.00	8680.00
11.0631950	7880.00	30380.00	1590.00	2940.00	4500.00	5690.00	23600.00	30510.00	42050.00	22570.00	29710.00	28180.00
11.0641951	3.68	1.43	.18	.01	.05	.08	1.13	1.51	176.00	26.10	3.93	4.02
11.0621951	258.00	8540.00	352.00	337.00	301.00	384.00	740.00	32400.00	65100.00	64000.00	42400.00	15300.00
11.0631951	9730.00	3160.00	22770.00	5460.00	5090.00	6480.00	21360.00	25330.00	36250.00	31690.00	27660.00	28360.00
11.0641952	3.77	1.18	.14	.11	.10	.16	.38	.17	821.00	584.00	38.60	1.92
11.0621952	965.00	286.00	348.00	330.00	307.00	484.00	1770.00	50700.00	53100.00	64300.00	62200.00	46300.00
11.0631952	14510.00	2930.00	4070.00	6210.00	4430.00	7080.00	22710.00	36530.00	48790.00	39480.00	26480.00	22290.00
11.0641953	3.45	2.36	.22	.31	.15	.32	.28	1.26	1.20	3.59	3.73	4.33
11.0621953	19200.00	284.00	302.00	322.00	289.00	379.00	2700.00	10400.00	56200.00	63800.00	45400.00	20300.00
11.0631953	29270.00	20370.00	3420.00	4550.00	3190.00	4360.00	13940.00	9260.00	29410.00	44610.00	25820.00	27250.00
11.0641954	4.05	1.56	.07	.08	.29	.38	.81	1.21	3.31	4.83	4.32	4.40
11.0621954	2770.00	266.00	251.00	304.00	360.00	382.00	795.00	40400.00	60900.00	63300.00	41500.00	21500.00
11.0631954	18200.00	4280.00	1700.00	1450.00	4020.00	7570.00	25600.00	35900.00	33100.00	20800.00	25800.00	20500.00

TABLE 13 - Continued:

11.0641955	4.14	1.84	3.05	2.98	2.97	3.10	3.14	1.33	5.11	5.56	5.83	4.40
11.0621955	4190.00	289.00	310.00	339.00	354.00	424.00	445.00	16100.00	52300.00	57400.00	59800.00	51100.00
11.0631955	17250.00	5770.00	2680.00	3270.00	3340.00	5550.00	10280.00	29270.00	45280.00	18700.00	6610.00	10150.00
11.0641956	3.84	3.10	3.77	3.38	3.58	3.53	3.48	4.85	144.00	• 447.00	10.70	7.54
11.0621956	25900.00	308.00	15400.00	637.00	375.00	755.00	842.00	17400.00	61800.00	64300.00	47400.00	43300.00
11.0631956	25370.00	25350.00	3310.00	25020.00	6210.00	11630.00	21000.00	45530.00	64910.00	54360.00	38880.00	10950.00
11.0641957	5.63	4.59	3.57	3.42	3.56	3.64	3.28	2.57	4.27	6.53	6.40	4.24
11.0621957	30000.00	5280.00	318.00	372.00	496.00	1620.00	1620.00	9140.00	59300.00	58600.00	51200.00	35500.00
11.0631957	18220.00	26820.00	6920.00	1840.00	3490.00	4530.00	11400.00	27870.00	55360.00	31640.00	14520.00	18090.00
11.0641958	3.10	3.14	3.06	2.21	2.22	2.19	2.45	2.89	774.00	257.00	11.00	8.03
11.0621958	13900.00	16400.00	1770.00	339.00	410.00	384.00	778.00	53000.00	61200.00	64300.00	55700.00	29300.00
11.0631958	23840.00	104.00	1823.00	4640.00	4900.00	6270.00	19500.00	34940.00	54550.00	51620.00	39300.00	33920.00
11.0641959	5.14	3.20	3.20	3.22	3.26	3.22	3.25	4.98	8.46	8.78	8.84	5.54
11.0621959	307.00	287.00	284.00	297.00	391.00	433.00	1680.00	14200.00	37200.00	31100.00	19700.00	370.00
11.0631959	31400.00	1800.00	1280.00	2120.00	3930.00	7560.00	18960.00	21640.00	17360.00	17050.00	15410.00	25410.00
11.0641960	4.77	3.12	3.11	3.15	3.23	3.30	3.32	4.29	6.03	6.67	7.03	5.17
11.0621960	440.00	233.00	242.00	255.00	284.00	378.00	787.00	23300.00	43000.00	29700.00	7100.00	235.00
11.0631960	3220.00	1390.00	748.00	1120.00	2520.00	6070.00	18450.00	16710.00	17850.00	23930.00	27140.00	8590.00
11.0641961	5.05	2.94	2.85	2.81	2.81	2.83	2.90	4.73	6.25	5.87	4.24	4.02
11.0621961	234.00	263.00	242.00	249.00	254.00	314.00	429.00	14199.00	29499.00	5109.00	349.00	508.00
11.0631961	1140.00	2150.00	2320.00	1190.00	2020.00	3480.00	12670.00	10040.00	20100.00	31810.00	14340.00	2710.00
11.0641962	3.87	3.34	3.40	3.40	3.50	3.48	3.88	3.90	6.40	8.32	7.47	6.50
11.0621962	253.00	276.00	263.00	284.00	351.00	485.00	826.00	1946.00	55196.00	59196.00	42596.00	16896.00
11.0631962	1590.00	1560.00	2620.00	2260.00	7250.00	6330.00	34120.00	45120.00	50390.00	51710.00	28620.00	28420.00
11.0641963	4.52	3.06	3.12	3.31	3.51	3.23	3.30	3.68	6.58	439.00	8.89	6.36
11.0621963	246.00	219.00	202.00	1382.00	312.00	845.00	482.00	9682.00	55892.00	64092.00	45292.00	30992.00
11.0631963	18840.00	1260.00	834.00	690.00	9600.00	5190.00	9830.00	43420.00	61240.00	47600.00	39950.00	20880.00
11.0641964	5.18	3.05	2.72	2.93	3.00	3.11	3.23	4.42	6.07	5.14	4.85	4.20
11.0621964	8822.00	332.00	272.00	271.00	258.00	337.00	596.00	23796.00	44896.00	33296.00	18796.00	236.00
11.0631964	27550.00	14700.00	4310.00	2540.00	2170.00	3230.00	10360.00	16930.00	24500.00	26000.00	21460.00	20210.00
11.0641965	3.82	3.56	3.88	3.27	3.01	3.04	2.90	3.45	5.91	8.39	8.48	6.40
11.0621965	506.00	3336.00	7236.00	376.00	385.00	374.00	1494.00	9014.00	40214.00	61014.00	49614.00	19814.00
11.0631965	813.00	68.00	8660.00	16010.00	6240.00	7250.00	16680.00	40350.00	52930.00	45610.00	48660.00	35870.00
11.0641966	4.92	3.62	3.49	3.24	3.26	3.40	3.55	4.51	5.96	6.36	5.58	3.39
11.0621966	284.00	429.00	380.00	343.00	352.00	716.00	3466.00	47216.00	62016.00	52216.00	33116.00	7726.00
11.0631966	21830.00	6550.00	4560.00	4730.00	3400.00	9280.00	30200.00	27630.00	25440.00	24850.00	27110.00	27750.00
11.1241922	24.00	21.00	43.00	120.00	125.00	205.00	680.00	3540.00	3910.00	1120.00	194.00	64.00
11.1241923	40.00	71.00	145.00	158.00	167.00	371.00	927.00	2680.00	1610.00	856.00	156.00	115.00
11.1241924	141.00	81.00	50.00	59.00	110.00	125.00	689.00	1110.00	148.00	49.00	21.00	13.00
11.1241925	28.00	165.00	159.00	143.00	325.00	589.00	1400.00	2830.00	1940.00	695.00	221.00	48.00
11.1241926	83.00	83.00	105.00	59.00	135.00	460.00	1960.00	1900.00	671.00	172.00	36.00	17.00
11.1241927	15.00	119.00	168.00	142.00	337.00	523.00	1230.00	2890.00	2650.00	667.00	122.00	42.00
11.1241928	67.00	310.00	110.00	112.00	149.00	713.00	1090.00	2390.00	913.00	196.00	46.00	16.00
11.1241929	11.00	17.00	22.00	31.00	55.00	224.00	522.00	1950.00	1040.00	258.00	56.00	25.00
11.1241930	17.00	14.00	29.00	44.00	131.00	329.00	1090.00	1330.00	1330.00	229.00	50.00	18.00
11.1241931	24.00	34.00	28.00	27.00	62.00	195.00	715.00	969.00	260.00	47.00	20.00	11.00
11.1241932	12.00	18.00	41.00	92.00	210.00	459.00	1110.00	2700.00	2800.00	781.00	126.00	32.00
11.1241933	22.00	19.00	19.00	24.00	45.00	152.00	773.00	1210.00	2120.00	350.00	62.00	21.00
11.1241934	15.00	19.00	51.00	91.00	145.00	538.00	956.00	699.00	446.00	95.00	33.00	19.00
11.1241935	37.00	127.00	118.00	152.00	272.00	302.00	1321.00	2831.00	2832.00	576.00	127.00	46.00
11.1241936	35.00	33.00	32.00	93.00	203.00	526.00	1754.00	2976.00	1915.00	624.00	108.00	35.00
11.1241937	27.00	27.00	63.00	56.00	246.00	324.00	1006.00	3660.00	2122.00	509.00	82.00	27.00
11.1241938	23.00	28.00	1166.00	202.00	260.00	492.00	1352.00	3815.00	4570.00	1611.00	361.00	153.00

TABLE 13 - Continued:

11.1241939	169.00	149.00	99.00	87.00	113.00	400.00	1430.00	1092.00	415.00	133.00	48.00	47.00
11.1241940	153.00	48.00	34.00	233.00	257.00	666.00	1502.00	3160.00	1756.00	335.00	74.00	29.00
11.1241941	23.00	28.00	131.00	172.00	248.00	447.00	721.00	3647.00	3154.00	1300.00	258.00	55.00
11.1241942	36.00	134.00	379.00	299.00	279.00	381.00	1200.00	2373.00	3393.00	1180.00	219.00	51.00
11.1241943	30.00	163.00	204.00	314.00	337.00	630.00	1836.00	2745.00	1774.00	675.00	147.00	47.00
11.1241944	32.00	33.00	39.00	63.00	100.00	252.00	567.00	2256.00	1411.00	515.00	98.00	35.00
11.1241945	23.00	139.00	161.00	136.00	468.00	277.00	1165.00	2412.00	2217.00	717.00	170.00	50.00
11.1241946	202.00	309.00	309.00	310.00	213.00	475.00	1640.00	2736.00	1431.00	434.00	111.00	58.00
11.1241947	116.00	155.00	228.00	157.00	216.00	428.00	1012.00	1947.00	639.00	148.00	45.00	27.00
11.1241948	107.00	93.00	43.00	105.00	69.00	119.00	559.00	2329.00	2437.00	451.00	72.00	27.00
11.1241949	24.00	27.00	29.00	37.00	55.00	123.00	1248.00	2370.00	1295.00	213.00	58.00	23.00
11.1241950	19.00	35.00	34.00	88.00	205.00	285.00	1507.00	2491.00	1559.00	309.00	58.00	31.00
11.1241951	38.00	1587.00	1666.00	445.00	430.00	499.00	1264.00	1873.00	1419.00	407.00	80.00	27.00
11.1241952	21.00	42.00	130.00	156.00	192.00	289.00	1471.00	4080.00	3199.00	1352.00	328.00	89.00
11.1241953	41.00	35.00	67.00	196.00	188.00	275.00	1106.00	1166.00	1763.00	695.00	98.00	36.00
11.1241954	23.00	32.00	45.00	37.00	152.00	434.00	1431.00	2280.00	893.00	232.00	52.00	22.00
11.1241955	14.00	30.00	85.00	83.00	128.00	220.00	573.00	1812.00	1589.00	289.00	57.00	21.00
11.1241956	14.00	25.00	1358.00	754.00	430.00	676.00	1413.00	3075.00	3385.00	1421.00	284.00	96.00
11.1241957	80.00	113.00	66.00	56.00	214.00	313.00	819.00	1795.00	2083.00	343.00	85.00	34.00
11.1241958	36.00	61.00	96.00	85.00	198.00	222.00	856.00	3904.00	3063.00	1114.00	355.00	135.00
11.1241959	42.00	32.00	28.00	96.00	165.00	388.00	1148.00	1144.00	641.00	115.00	38.00	175.00
11.1241960	54.00	24.00	19.00	26.00	107.00	359.00	1137.00	1449.00	788.00	147.00	40.00	19.00
11.1241961	19.30	42.50	69.20	41.60	114.00	183.00	786.00	1003.00	631.00	115.00	67.40	26.50
11.1241962	19.60	25.30	61.60	66.50	249.00	229.00	1826.00	2027.00	2353.00	648.00	125.00	38.70
11.1241963	53.40	31.90	35.60	127.00	1001.00	345.00	575.00	2519.00	2478.00	898.00	185.00	68.10
11.1241964	47.40	238.00	157.00	98.40	114.00	174.00	679.00	1442.00	984.00	218.00	62.90	22.70
11.1241965	16.90	114.00	1348.00	556.00	427.00	474.00	1030.00	2410.00	2553.00	1140.00	409.00	103.00
11.1241966	43.10	211.00	166.00	150.00	144.00	462.00	1568.00	1888.00	564.00	153.00	79.40	21.90

OUTPUT DIRECT FROM SUBROUTINE TARCOT

OBSERVED VALUE OF STATISTIC = 3.74
T-TEST SHOWS SIGNIFICANCE AT THE(99 PERCENT) LEVEL

VALUE OF T AT THE(95 PERCENT) LEVEL = 2.02

VALUE OF T AT THE(98 PERCENT) LEVEL = 2.42

VALUE OF T AT THE(99 PERCENT) LEVEL = 2.70

END OF OUTPUT FROM SUBROUTINE TARCOT

END OF ALL RUNS

SIGNATURE,H.J.MOREL-SEYTOUX

APRIL 30,1968,DEPT. OF CIVIL ENGINEERING,HYDROLOGY PROGRAM,COLORADO STATE UNIVERSITY

RESEARCH SPONSOR . U.S.BUREAU OF RECLAMATION, OFFICE OF ATMOSPHERIC WATER RESOURCES RESEARCH

Key words: Weather modification, Runoff, Evaluation, Mountain basins, Water yield, Suitability, Upper Colorado River Basin, Hydrology, Data.

ABSTRACT: Fundamentally the project was concerned with answering two questions: (1) How surely can weather modification be considered responsible for observed increases in runoff? (2) What makes a basin more suitable to a weather modification operation than another?

Tests were devised to answer the first question. Utilizing a target-control concept the tests indicate that six years or less would be sufficient to detect a 10% increase in seasonal runoff for about one-third of all gaged basins in the Upper Colorado River Basin.

Suitability criteria for both large water gain and rapid evaluation have been developed. Their application to the Upper Colorado River Basin point to three optimal zones of approximately 30 miles radius, centered around Red Mountain (half way between Silverton and Ouray), Marble (or more precisely half way between Marble and Crested Butte) and Vail.

Reference: H. J. Morel-Seytoux , Final Report for FY 1966 and 1967, Prepared for Bureau of Reclamation, Office of Atmospheric Water Resources, Denver, Colorado - Project SKYWATER, "Suitability of Basins to Weather Modification and Statistical Evaluation of Attainment, Colorado State University, Fort Collins, Colorado. Hydrology Program Report No. CER68-69HJM5 Parts 1, 2, 3, 4. July 1968

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Suitability criteria for both large water gain and rapid evaluation have been developed. Their application to the Upper Colorado River Basin point to three optimal zones of approximately 30 miles radius, centered around Red Mountain (half way between Silverton and Ouray), Marble (or more precisely half way between Marble and Crested Butte) and Vail.

Reference: H. J. Morel-Seytoux , Final Report for FY 1966 and 1967, Prepared for Bureau of Reclamation, Office of Atmospheric Water Resources, Denver, Colorado - Project SKYWATER, "Suitability of Basins to Weather Modification and Statistical Evaluation of Attainment, Colorado State University, Fort Collins, Colorado. Hydrology Program Report No. CER68-69HJM5 Parts 1, 2, 3, 4. July 1968

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