SUITABILITY OF BASINS TO WEATHER MODIFICATION AND STATISTICAL EVALUATION OF ATTAINMENT

Interim Report for Period July 1, 1968 -
December 31, 1969

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PROJECT SKYWATER

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HYDROLOGY PROGRAM
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ABSTRACT

The objective of the ongoing research is to develop definite mathematical techniques to evaluate or predict the hydrologic results of actual or hypothetical atmospheric water resources programs.

Work performed to date has yielded very positive results. Three different techniques utilizing runoff show that the chances of significant evaluation of the Colorado River Basin Pilot Project for the planned four or five years of operations are very high.

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A. INTRODUCTION

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 of Colorado State University, for the period July 1, 1968 to December 31, 1969.

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

3. To document in detail the various aspects of the work done, and

4. To briefly state the work planned for the next period, January 1, 1970 to June 30, 1971.

B. OBJECTIVES AND MAJOR RESULTS OF PROGRAM

The Colorado State University Hydrology Program has two clearly defined objectives. They are the development of definite techniques to:

1. determine the hydrologic suitability of regions considered for precipitation management and,

2. evaluate the results of future programs in general and of the Colorado River Basin Pilot Project [1,2] in particular.

Work performed has yielded very positive results. Three different techniques utilizing runoff show that the chances of significant evaluation of the pilot programs for the planned four or five years of operation are very high. Assuming that a uniform 10% increase in winter precipitation is induced by the precipitation management program, it was found that 3 and 6 years of operations for the Northern* and Southern areas respectively (see Figures 1 and 2) would be necessary for evaluation at the 95% significance level and 50% power. However, past experiments in these areas indicate that if 10% is a reasonable estimate for the Northern area, a 30% increase is more likely for the Southern area [3]. In addition, the operations in these areas will most probably be randomized on a 60-40 basis. Under these conditions adjustment of the previously quoted numbers 3 and 6 years leads to the results that 9 and 3 years would rather be needed. This means that for a five years plan of operations the chances of obtaining significance in the Southern area are very good, i.e., much better than 50%. On the other hand the corresponding chances in the Northern area are much less than 50%.

These results suggest from a strict water resources evaluation point of view that randomized operations be conducted in the South and non-randomized ones be conducted in the North.

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*In 1968, the Bureau of Reclamation adopted a plan to start pilot programs for weather modification operations in the Upper Colorado River Basin and two regions were selected for this purpose [1]. The first was the Upper Basin of the Colorado River ** which will for brevity be referred to in this report as the Northern Project area (Fig. 1). The second area was the San Juan Mountains region referred to as the Southern Project area (Fig. 2). Since the initiation of the study,, the plans of the Bureau were modified. Currently [2] only one area is considered: the Southern area. Nevertheless, because they had already been calculated, the results for the Northern area are also reported.

**The reader is warned for possible confusion. In this report the expression "Upper Colorado River Basin" refers to the Colorado Basin above Lee's Ferry. On the other hand, the expression "Upper Basin of the Colorado River" refers to a much smaller drainage basin including the main stem of the Colorado close to its source and a few tributaries. The limits of that basin are shown on Fig. 1.

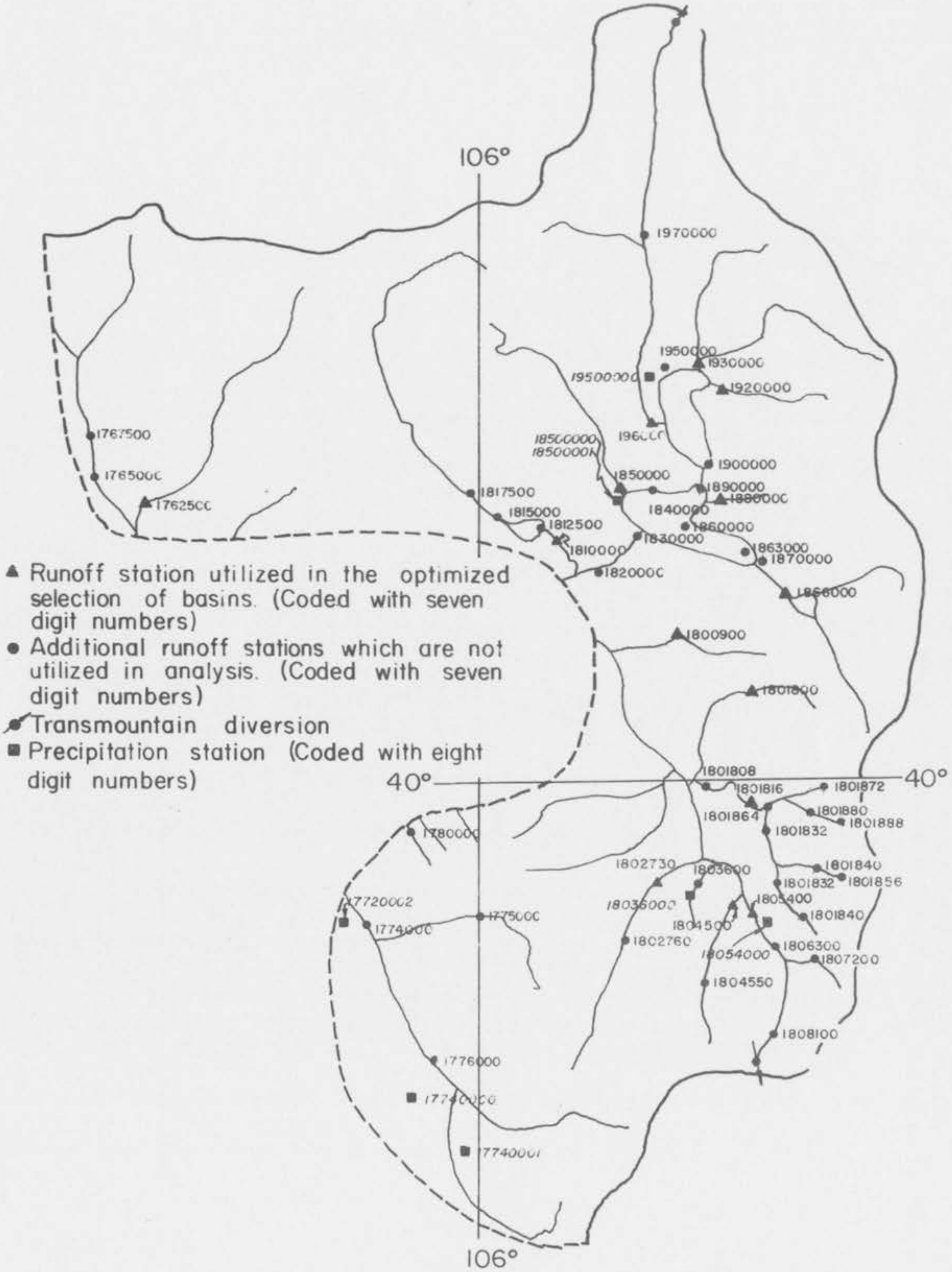

Fig. 1. General configuration of and location of gages within the Upper Basin of the Colorado River

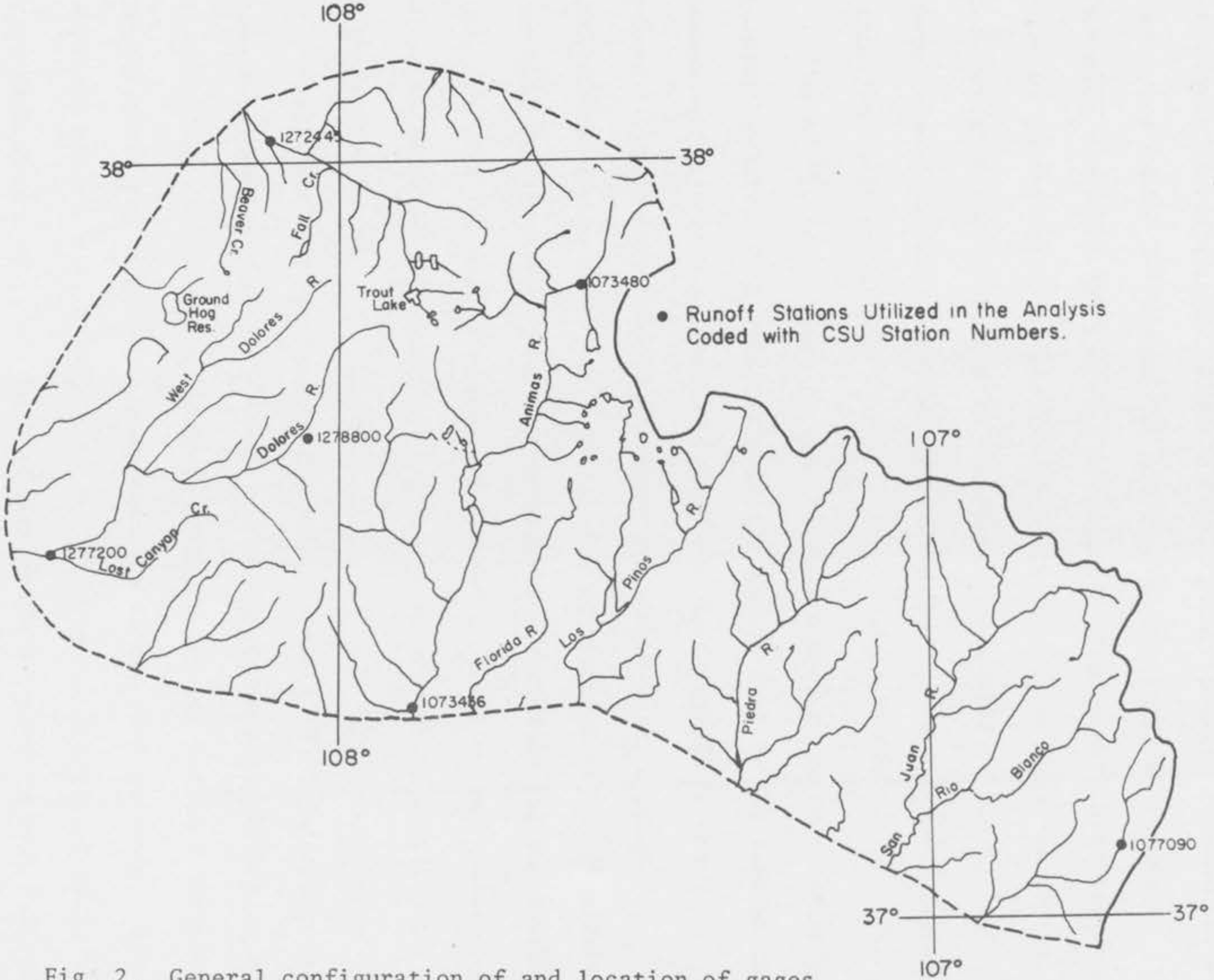

Fig. 2. General configuration of and location of gages within the Colorado River Basin Pilot Project area

C. WORK DIVISIONS AND RELATION TO OBJECTIVES

The major effort of the program focused on the development of techniques of evaluation. Results from a prior contract (4) indicated that years needed for evaluation would be in the range of 10 years (assuming a uniform 10% increase in runoff). The results were based on a target-control test for individual basins, using seasonal runoff as a test variable and for basins in the Upper Colorado River Basin. It seemed almost natural to investigate extensions of the method. Several extensions were possible.

One of the first ideas to come to mind concerns the test variable: seasonal runoff. With that variable the sample size is the same as the number of years of experiments. Could not daily runoff be used? A priori it would tremendously increase the sample size, a prime determinant factor in the efficiency of a statistical test. It turned out that the improvement was not as high as anticipated but the results indicate that the method reduces the number of years on the average by a factor of three (5) which is of course a result of high practical significance.

Again the work done during the prior contract (4) considered evaluation for individual basins. Would not the efficiency of evaluation be increased by considering a group of basins? Because within a large region there are many sub-basins this led to the next question: how does one select, say, 6 basins out of 15 to insure positive results in a minimum amount of time? What weight should be given to each individual basin within the combination? Fundamentally the low efficiency of the two-sample tests is due to the high natural variability of runoff. A procedure was developed (6) to select a combination of basins with minimal variation. Application of the technique has indicated that

3 and 6 years for the Northern and Southern areas respectively would be needed (assuming a uniform 10% increase in winter precipitation).

Finally a direct extension was carried. Retaining seasonal flow as a test variable and the concept of a target and control, the new procedure considers the multiple targets and controls case. The value of this technique lies primarily in its realistic character for evaluation of large scale operational programs.

Subsidiarily another division of effort was pursued. It is concerned with the design and implementation of a computerized and efficient data system.

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

D. DAILY RUNOFF AS A TEST VARIABLE

Daily runoff would a priori seem to be a better variable for evaluation than seasonal runoff because so many more observations are available per year. Unfortunately sequential observations of daily flow are not independent. To utilize this variable in the target control conditional Student's t-test, only independent observations can be used. To obtain a proper set of independent daily runoff observations the stochastic structure of daily runoff has to be established. Studies of many high elevation stations in Colorado have shown that (1) independence could only be secured during the rising limb of the hydrograph, and (2) that a lag time of 20 days between observations was required during that period. That lag is the same for all the stations in Colorado, and seems also valid for California's high elevation stations. The correlation coefficient between target and control is always lower for daily runoff than for seasonal runoff. This is a negative result. Nevertheless the efficiency of the target-control test is improved on the average by a factor of three. Sample of results is shown in Table 1. (The complete results are given in Appendix 2).

One area of future worthwhile investigation lies in the development of a test that does not require independent observations. With such a test the full potential of daily runoff might be realized.

E. OPTIMAL GROUPING OF BASINS

The problem of selection of basins for evaluation can be formulated as follows:

Given a large region consisting of N (say 12) basins and the fact that only a smaller number of them, n (say 5) can be used for evaluation for economic reasons, what is the best way to select them to insure minimal time evaluation?

It has been shown previously (4) that in the case of evaluation using a single basin (case $n = 1$) the basin to be selected should be the one with minimum value of the ratio C/E where C is the runoff coefficient of variation and E the expected percentage increase.

Indeed, the pilot project areas involve many sub-basins within their boundaries. In this case, it is advisable to choose a favorable combination of sub-basins for evaluation. For this purpose, a new variable Q^* is constructed by a linear combination of n runoff variables, Q_i $(i = 1, 2, \ldots, n)$, i.e.,

$$Q^* = \alpha_1 Q_1 + \alpha_2 Q_2 + \ldots + \alpha_n Q_n = \sum_{i=1}^{n} \alpha_i Q_i \qquad (1)$$

TABLE 1

NUMBER OF YEARS REQUIRED FOR THE DETECTION OF A 10% INCREASE IN THE MEANS AT THE 95% LEVEL

Identification		Correlation coefficient with		Target coefficient of variation		Number of years for significance using		
Target	Control	Daily flows	Seasonal flows	4 months period	6 months period	4 months Seasonal flows M4(yr)	6 months Seasonal flows M6(yr)	Daily flows Md(yr)
12	18	.710	.728	.246	.255	11	12	5
12	19	.798	.940	.246	.255	3	3	G.T.20
12	22	.730	.807	.246	.255	8	9	3
12	30	.701	.785	.246	.255	8	10	10
16	18	.806	.969	.515	.504	6	6	1
18	12	.710	.728	.575	.537	62	54	5
18	16	.806	.969	.575	.537	8	7	G.T.20
18	21	.732	.811	.575	.537	45	39	G.T.20
18	30	.796	.877	.575	.537	30	27	3
19	12	.798	.940	.313	.312	4	4	1
19	22	.761	.792	.313	.312	15	14	2
21	18	.732	.811	.572	.510	45	35	1
21	30	.722	.848	.572	.510	37	29	10
22	12	.730	.807	.338	.326	16	15	2
22	19	.761	.792	.338	.326	17	16	G.T.20
22	30	.720	.914	.338	.326	8	7	8
30	12	.701	.785	.428	.413	28	26	6
30	18	.796	.877	.428	.413	17	16	4
30	21	.722	.848	.428	.413	20	19	4
30	22	.720	.914	.428	.413	12	11	4

6 months: March-August
4 months: April-July
G.T. means greater than.

Where Q_i is the runoff from an individual sub-basin. Much freedom is gained from a combination of runoff variables from various basins such as (1) compared to the use of a single basin runoff. The freedom gained is twofold. First, there is freedom gained in the process of selecting n basins among many. For example, where there are 15 ways of selecting one basin out of 15, there are 3003 ways of selecting five basins out of 15. Second, there is freedom gained in the process of selection of the parameters α_i once n sub-basins have been chosen.

The procedure is to minimize the C/E ratio of the combination subject to a few constraints of a hydrologic nature. The constraints require that the expectation of the random variable Q* be the mean of the total runoff for the group of n basins, and that the expected increase of the mean of Q* be that of the total runoff for the group of n basins.

The efficiency of the procedure is illustrated in Figure 3 and in Table 2. (The complete results are given in Appendix 3).

One area of future worthwhile investigation lies in the determination of the reliability of the calculated number of years. Whereas this number decreases with the size of the combination, its reliability also decreases. In a certain sense an optimal size must exist at which the additional decrease in the calculated number of years is not worth the added variability and therefore risk.

F. MULTIPLE TARGET-CONTROL TEST

The advantage of such test using seasonal flow lies primarily in its realistic character. There are indeed many targets and many controls in large regions such as the pilot project area. Truthfully there are too

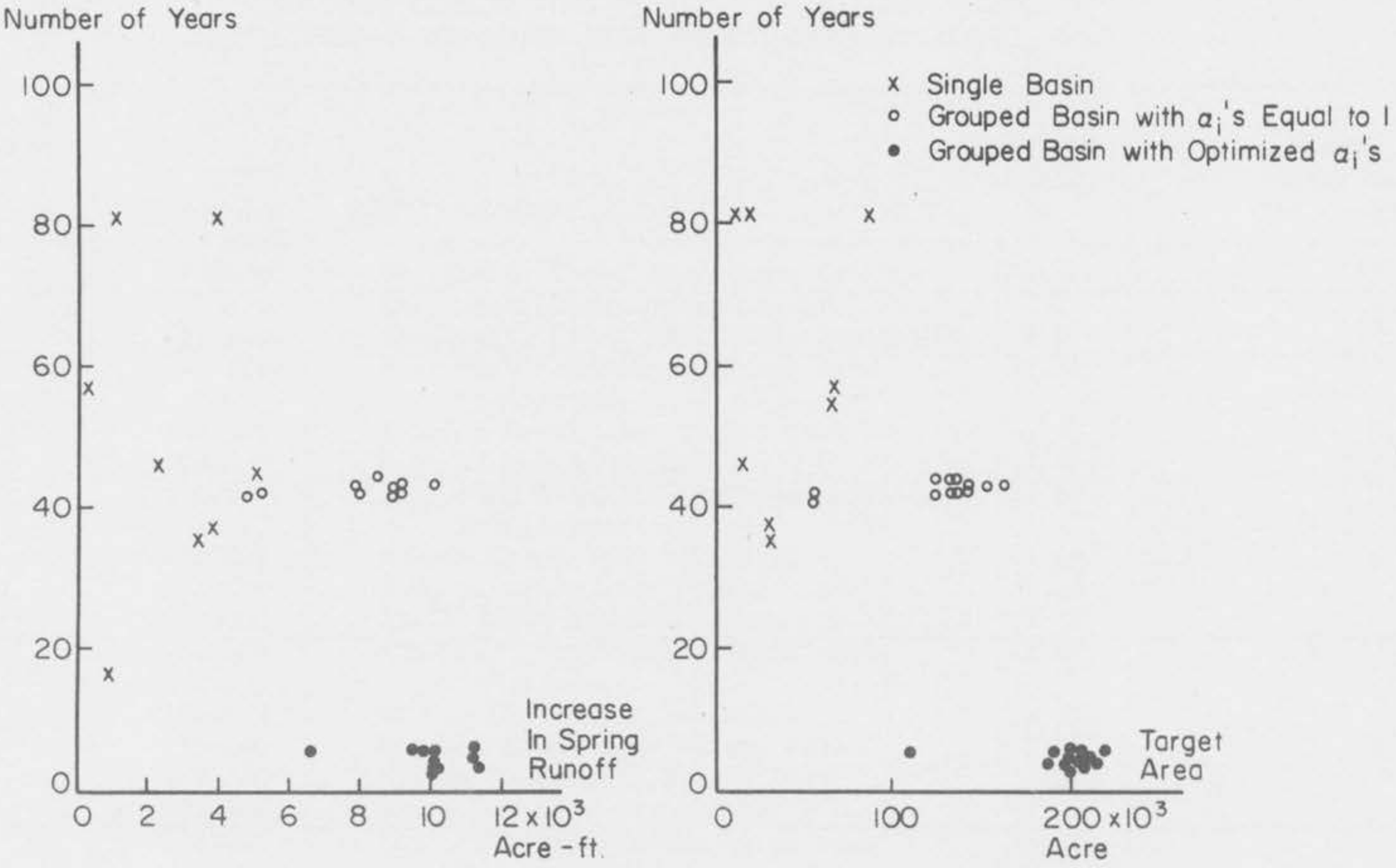

Fig. 3. Minimum number of years needed for evaluation for combinations of two through six sub-basins out of 14 in the Upper Basin of the Colorado River

TABLE 2

OPTIMAL COMBINATIONS OF GAGES FOR VARIOUS GROUP SIZES IN THE UPPER BASIN OF THE COLORADO RIVER

Number of Sub-basins in Combination	CSU ID	Name	Weight Factor α	Number of Years Needed for Evaluation
1	1850000	Stillwater Creek above Lake Grandby	1.0	17
2	1800900	Strawberry Creek near Grandby	1.0	32
	1850000	Stillwater Creek above Lake Grandby	1.0	
3	1762500	East Fork Troublesome Creek near Troublesome	-2.38	8.2
	1804500	Vasquez Creek near Winter Park	.59	
	1930000	North Inlet at Grand Lake	2.39	
4	1762500	East Fork Troublesome Creek near Troublesome	-1.83	6.0
	1801800	Meadow Creek near Tabernash	-4.00	
	1804500	Vasquez Creek near Winter Park	.14	
	1930000	North Inlet at Grand Lake	3.10	
5	1762500	East Fork Troublesome Creek near Troublesome	-3.60	3.8
	1801800	Meadow Creek near Tabernash	-6.99	
	1804500	Vasquez Creek near Winter Park	2.67	
	1810000	Willow Creek near Winter Park	.34	
	1930000	North Inlet at Grand Lake	4.15	
6	1762500	East Fork Troublesome Creek near Troublesome	-3.37	2.9
	1801800	Meadow Creek near Tabernash	-5.45	
	1801816	Ranch Creek near Frazer	-2.31	
	1804500	Vasquez Creek near Winter Park	3.60	
	1810000	Willow Creek below Willow Creek Reservoir	.07	
	1930000	North Inlet at Grand Lake	4.51	

many. Again the real problem in the selection of several targets and controls among many possible candidates. Two techniques were investigated and applied for that purpose: principal components and canonical variables analysis. For minimal time evaluation the latter is more effective. Table 3 illustrates the results. It shows that for purpose of evaluation a pair of combinations, the optimal pair, is more effective than several but it is not as representative. (The complete results are given in Appendix 4).

One area of worthwhile future investigation lies in a study of the sensitivity of the results to fluctuations in various parameters.

G. HYDROLOGIC DATA SYSTEM

The effort was a continuation of a previous contract work. Daily runoff data were added in a limited way to the system. Also a data collection work was initiated for the headwaters of the Rio Grande and tributaries. The additional collection is limited to stations within the state of Colorado.

H. CONCLUSIONS

The work effort was rather rewarding. Several techniques of evaluation have shown their value and their applicability. They show that a positive hydrologic evaluation can be achieved for the Colorado River Basin Pilot Project within the planned four or five years of experiments with a high probability.

Work remains to be done to ensure complete rigor in the new procedures, to test their general applicability and sensitivity. These techniques

TABLE 3

MINIMUM NUMBER OF YEARS TO DETECT THE INCREASE OF 10 PERCENT IN RUNOFF MEANS USING CANONICAL VARIABLES

Type	No. of canonical variables in target	No. of canonical variables in control	Value of $\underline{\mu}'\underline{V}^{-1}\underline{\mu}$	τ^2	Minimum number of years to detect the increase, N*	Remarks
N-CN-4	1	1	5.037	5.468	3	The minimum value of N* is obtained from the larger of N* = τ^2 $\underline{\mu}'\underline{V}^{-1}\underline{\mu}$ or N* = k+1 where k is the total number of variables in both target and control.
	2	2	5.197	7.640	5	
	3	3	5.198	9.646	7	
	4	4	5.368	11.655	9	
N-CN-6	1	1	5.877	5.468	3	
	2	2	6.040	7.640	5	
	3	3	6.060	9.646	7	
	4	4	6.124	11.655	9	
S-CS-4	1	1	1.271	5.468	5	
	2	2	1.305	7.640	6	
	3	3	1.388	9.646	7	
	4	4	1.581	11.655	9	
S-CS-6	1	1	1.423	5.468	4	
	2	2	1.465	7.640	6	
	3	3	1.690	9.646	7	
	4	4	1.752	11.655	9	

were developed in parallel and independently. Better results can probably be achieved by integrating them into a single technique.

I. WORK PLANNED FOR PERIOD JANUARY 1, 1970 - JUNE 30, 1971

In a meeting with Mr. P. Hurley and Mr. D. James of the Office of Atmospheric Water Resources, on October 23, 1969 a work plan for the second half of the contract period was discussed. This work plan calls for:

a. Careful selection of fairly large rivers, within the San Juan Mountains area (Colorado River Basin Pilot Project area) to be used for evaluation, e.g. Piedra, San Juan, Animas, Tomichi, etc.

b. Gathering of all pertinent hydrologic information on these watersheds.

c. Application of all evaluation techniques developed under the contract to these rivers and determination of tables of probability of attainment of statistical significance as a function of the parameters (e.g. 4 or 5 years of operation, 5, 10...30, 35% increase in runoff, etc.)

d. Study of the effect of basin geometry and other characteristics on the evaluation techniques.

e. Documentation of the recommended technique of evaluation in a step by step procedure readily usuable by the contractors of the evaluation.

J. REFERENCES

1. Bureau of Reclamation, U. S. Dept. of the Interior, "Reclamation to conduct Project Skywater Program in Colorado Rockies this winter," September 22, 1968, pamphlet.

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3. Bureau of Reclamation, U. S. Dept. of Interior, "Installation and Operation of an Opportunity Recognition and Cloud Seeding System for Operational Weather Modification Research in Colorado," Colorado River Basin Pilot Project, Atmospheric Water Resources Program, October 1969.

4. Morel-Seytoux, H. J., "Suitability of Basins to Weather Modification and Statistical Evaluation of Attainment," Final report for the Bureau of Reclamation, Hydrology Program, Colorado State University, Fort Collins, Colorado, 1967, Part 1, 62 p.

5. Dumas, A. J. and Morel-Seytoux, H. J., "Statistical Discrimination of Change in Daily Runoff," Colorado State University Hydrology Paper No. 34, August 1969.

6. Nakamiche H. and Morel-Seytoux, H. J., "Suitability of the Upper Colorado River Basin for Precipitation Management," Colorado State University Hydrology Paper No. 36, October 1969.

7. Nimmannit V. and Morel-Seytoux, H. J., "Multivariate Analysis of Hydrologic Changes." Colorado State University Hydrology Paper, No. 37, November 1969.

Appendix 1

PERSONNEL

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1. Dr. Hubert J. Morel-Seytoux, Associate Professor of Civil Engineering, Principal Investigator for the duration of the contract (July 1, 1968 - June 30, 1971).

2. Mr. Andre J. Dumas, M.S. graduate of Colorado State University, Civil Engineering Department. Mr. Dumas was responsible for the study of statistical discrimination of change in daily runoff (July 1, 1968 - January 31, 1969).

3. Mr. Hiroshi Nakamichi, M.S. graduate of Colorado State University, Civil Engineering Department. Mr. Nakamichi was responsible for the study of suitability of the Upper Colorado River Basin for Precipitation Management (July 1, 1968 - August 31, 1969).

4. Dr. Viboon Nimmannit, Ph.D. graduate of Colorado State University, Civil Engineering Department. Dr. Nimmannit was responsible for the study of regional discrimination of change in runoff (July 1, 1968 - September 30, 1969).

5. Dr. Richard L. Brustkern, Ph.D. graduate of Colorado State University, Civil Engineering Department. Research Associate. Dr. Brustkern is responsible for the Hydrologic Data System (January 1, 1970 - June 30, 1970).

6. Dr. Mike Behbehani, Ph.D. graduate of Colorado State University, Department of Physiology and Biophysics. Research Associate Dr. Behbehani is responsible for the computer operations (Jan. 1, 1970 - June 30, 1970).

7. Mr. Jungkeun Sonu, graduate student (January 1, 1970 - June 30, 1971).

Appendix 2

STATISTICAL DISCRIMINATION OF CHANGE IN DAILY RUNOFF

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by

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August 1969

HYDROLOGY PAPERS
COLORADO STATE UNIVERSITY
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STATISTICAL DISCRIMINATION OF CHANGE IN DAILY RUNOFF

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HYDROLOGY PAPERS
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ACKNOWLEDGMENTS

The present paper is based primarily upon Mr. Andre J. Dumas' Master of Science Thesis in the Department of Civil Engineering, Colorado State University entitled, "Detection of a Change in Watershed Response by a Stochastic Analysis of Daily Streamflows." The work was supported by the U.S. Bureau of Reclamation, Contract numbered BR 14-06-D-6597, whose help is gratefully acknowledged.

The U.S. Geological Survey, Water Resources Division, Automatic Data Processing Unit, supplied the daily flow data. Their gracious cooperation is acknowledged.

RELATION OF HYDROLOGY PAPER NO. 34 TO RESEARCH PROGRAM: "HYDROLOGY OF WEATHER MODIFICATION"

The present study is part of a more comprehensive project which has as one of its objectives the development of methods of evaluation of atmospheric water resources programs. Correlatively the application of the methods to a variety of basins forms a basis for selection of suitable watersheds, basins or regions.

Several approaches are possible and are pursued. This report discusses one of them. Two other approaches will be discussed in forthcoming papers with tentative titles, "Suitability of the Upper Colorado River Basin for Precipitation Management" and "Multivariate Discrimination of Change in Seasonal Runoff."

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ABSTRACT

The purpose of this study was the development of a technique for rapid detection of the occurrence of a suspected hydrologic change in high mountain watersheds. A method has been developed that uses a sequence of independent daily flows.

This procedure is superior to previous ones based on seasonal or yearly flows. The results of this investigation show the use of daily, instead of seasonal flow, data in a Student t-test reduces the number of necessary years of data for detection by an average of five in 14 out of the 20 cases studied, or by an average of three for the 20 cases. All of the cases come from the Upper Colorado River Basin. The study is particularly relevant to the planned cloud seeding operations of the Bureau of Reclamation in high elevation areas of the Colorado Rocky Mountains.

The statistical procedure of detection relies on the Target Control concept and the application of a conditional Student t-test, a test of the difference between the adjusted means obtained by the regression lines between Target and Control for the seeded and non-seeded periods.

STATISTICAL DISCRIMINATION OF CHANGE IN DAILY RUNOFF

by

Andre J. Dumas* and Hubert J. Morel-Seytoux**

Chapter I

INTRODUCTION

1.1 Water resources planning. The increasing demand, and in some parts of the world the desperate need for water, has almost inevitably led men in positions of responsibility to be concerned with the problem of water shortage in particular and of water resources in general [1]. Planning of water resources had, until the relatively recent past, been confined primarily to the task of redistribution in space and time of the naturally available water, or to the task of better utilization and reutilization. It is only recently that the idea [2] of increasing the water supply beyond the natural yield of the hydrologic cycle has started to be realized. At present at least two engineered means of increasing the water supply seem to hold promise for the near future: ocean water desalination [3] and precipitation management [4].

The water situation is particularly critical in the Colorado River Basin. The Colorado River system is the largest in the United States that flows mainly through lands with a chronic water deficiency for cultivation of crops [5]. The average specific (or unit) yield of the Lower Colorado River Basin is only 0.3 inches, the lowest yield in the United States for a drainage area of this size [5]. (Unit yield is the depth, in inches, of the cumulative volume of flow during a given period, in this instance a year, when volume is spread uniformly over the whole watershed.) The Upper Colorado River Basin does not yield much better, 2.2 inches. It outranks only a few basins, the Rio Grande and the Missouri basins, but it is far below the Mississippi's 10 inches and the Columbia's 16 inches. Since the 1940's, the basin's population has increased rapidly with an accompanying growth in demand on the region's water resources for irrigation, industrial and domestic uses [6]. Over the decade from 1951 to 1960, the population of the five states comprising the Upper Colorado River Basin has increased by 40 percent, while over the same period the population of the nation as a whole has increased by only 20 percent [7]. Population projections and the associated water demands indicate a need for actual importation of approximately 3 million acre-feet annually by the year 2080 [8]. Development of the vast oil-shale resources alone would require an additional 1 million acre-feet by the year 2000, assuming a daily oil production of four million barrels [5,8]. "This amount of water simply is not there now." [8] Although "the Colorado Basin is closer than most other basins in the United States to utilizing the last drop of available water for man's needs."[5]

Of course there are alternatives to importation to meet these demands: better utilization, reutilization, desalination and precipitation management. Prohibition by Congress to undertake studies of importation schemes for the next ten years emphasizes the serious need for considering the alternatives. Desalination in the Upper Colorado River Basin appears largely unfeasible at present. The lowest quoted cost estimate suggests water in southern California may cost $35 per acre-foot at the source, with storage, transport, and delivery costs additional [5], and of course it is uphill all the way! Within 400 miles from the source it is estimated the cost would have risen to $120 [8]. On the other hand the cost of water produced by cloud seeding winter storms, from ground-based silver iodide nuclei generators, is estimated at roughly $2 per acre-foot, and under full scale operations it is estimated an average additional 1.9 million acre-feet would appear annually in the rivers [9]. The potential economic and quantitative significance of precipitation management is now reasonably well established.

1.2 Evaluation of atmospheric water resources attainments. Successful water resources management in this field requires techniques for detection and measurement of the increase in water yield induced by weather modification. The main difficulties in this evaluation are caused by (a) the natural variability of hydrologic variables which exceeds the expected range of the increase induced by man, and (b) the inaccuracy of the discharge measurements. Simple statistical tests have been developed [10]. They have not proven very sensitive and, as a result, require long periods of observations, prior to and during seeding operations, in order to give satisfactory test results. Furthermore, these tests are insensitive when experiments are performed during a dry period of annual stream flow sequences. Therefore, more sophisticated techniques were needed. The target control concept was introduced, and different tests were devised [10], including a Chi-square test and a Student-t test. In a recent study [11], a target-control Chi-square test was applied to the mean annual or mean seasonal flows of some rivers and it was shown the number of years M(or sample size) necessary to detect, at the 95% level of significance and 50% power a given percentage h of increase in the yearly or seasonal flows was:

$$M = 4(1-\rho^2)\,\frac{C^2_{v,T}}{h^2} \qquad (1)$$

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**Associate Professor of Civil Engineering, Colorado State University, Fort Collins, Colorado.

where ρ is the correlation coefficient between the target and the control watersheds, and $C_{v,T}$ is the coefficient of variation of the target watershed. Calculations were performed for a few stations in the Upper Colorado Basin to get 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 was calculated [11]. The results are shown in Table 1. The results are encouraging though still too high. The best results, 4 and 6, have to be discounted largely because of the proximity of the target and control and the resulting quasi-impossibility to prevent contamination. What then can be done to reduce the number of years needed to obtain significance?

TABLE 1

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, BASED ON SEASONAL RUNOFF

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

There are several avenues open to answer this fundamental question. One avenue is to improve the test to which the data are subjected. It was not promising. Another avenue consists of grouping observations in some favorable manner for several targets, or better, for several targets and controls. Both avenues are presently being pursued. The last avenue, which is the subject of this study, looks for an optimal test variable, given the test, i.e., a single target-control conditional Student's t-test [11].

First one must answer the following question: which variable, annual, seasonal, monthly or daily runoff, is a better detector? Theoretically this question has been answered, in general and the daily runoff variable is the most promising. The basic underlying idea is that the shorter the time interval --by which the time series of river streamflow is divided into a discrete time series--the more information one will derive. (Daily flow is defined in this study as the average daily runoff at a section of river, the averaging being done either from a continuous record of an automatic recorder or from river stage measurements taken at representative time intervals to make interpolation and averaging consistent.) From a practical point of view, however, it is not so clear cut because the power of the detection procedure depends not only on the sample size, but also on the variability of the runoff (which increases as the unit of time decreases), the magnitude of the measurement error, the degree of correlation between the variable in the watershed of interest and a control watershed, the physical nature of the suspected cause of the change in runoff, and the magnitude of the resulting effect. The purpose of this study was to initiate a preliminary investigation of the practical value of daily runoff for evaluation. The qualified conclusion of the study is that, indeed, it has practical merit.

Chapter II

THE TARGET-CONTROL CONDITIONAL STUDENT'S t-TEST

2.1 An optimization problem in detection. The problem of early detection of a change in watershed runoff received impetus as controversy characterized the field of weather modification. Early weather modification experiments were conducted without much care for the statistical design of the experiments. In an early stage of a new science this oversight is understandable. What purpose is it to draw tables of the number of years for significance at a given level versus all possible hypothetical percentage increases, if even the order of magnitude of that increase is totally unknown? The availability of the table would not have affected the decision to proceed with the experiments. On the other hand, once the order of magnitude of the increase is known, the table becomes crucial. It is crucial because the percentage increase in runoff turns out to be small, on the order of 10%. Careful inspection of the table becomes a requirement in the design of new experiments. It may lead to a variety of questions; e.g., will it be possible to show significance at say the 90% level within the contemplated five years of experiments? If not, can significance be attained by shifting the experiments to a different location? If not...well, how good was the table in the first place?

At this point it is necessary to state clearly the objective of a method of detection. For different objectives different methods will be required. Ideally one wants to find the technique that will permit one to ascertain, in the minimum amount of time, that an identified cause, e.g., cloud seeding, has affected a selected measure of watershed response at a chosen significance level. Once that technique has been found, it becomes possible to calculate the number of years needed for significance at a given power. (The power is the probability that significance will be attained within this number of years.) This number of years depends on several parameters, the chosen significance level, the chosen power, the degree of certainty of identification of the cause (i.e., is cloud seeding really responsible for the detected change?), the selected response (e.g., hourly precipitation, monthly runoff), the characteristics of the watershed (i.e., the nature of the transfer function between cause and effect), and the magnitude of the change in watershed response. Ideally one would like to find the technique for which the calculated number of years is minimum for all possible values of the previously listed parameters....It cannot be done....Even less ambitious optimization problems cannot receive a general solution. A technique will be optimal for a certain range of parameters but not for others [12]. One is therefore forced to limit the original ambition to a more realizable level. Besides, the optimization problem will not present itself usually in this unconstrained form. The detection scheme must be compatible with a variety of restraints of diverse nature. For example, from a statistical point of view the target-control pair Dolores-Hermosa (line 3 of Table 1) would be ideal. However, the accuracy of targeting with ground-based generator is not sufficiently developed to permit such a close control.

Short of overall optimization one must settle for suboptimization. Of course once this step is taken, and there is no other choice, there is an infinite variety of possible options. As discussed in the Introduction there are several avenues for research. In the present study the following suboptimization problem was considered. Given that the cause of a suspected change has been identified (be it cloud seeding, timber cuts, etc.)--that its effect can be measured as runoff, that the statistical technique to which the data will be subjected is the single target-control conditional Student's t-test--what is the optimal test variable, seasonal or daily runoff? This is the problem.

It is a much restricted problem in appearance but an important practical one. This assertion is validated by the conclusion of the study. Without the benefit of the conclusion it could nevertheless be inferred a priori from the following heuristic reasoning. In the limited number of cases for which formulae are actually available to calculate the number of years, this number is inversely proportional to the number of data per year. Using daily flow versus a four-months seasonal flow could therefore bring a reduction by two orders of magnitude. One expects a greater variance for daily flow. Because the number of years is proportional to this variance, one expects a reduction in the potential gain from using daily flow. Similarly the expected decrease in the coefficient of correlation between target and control will further limit the gain. It is difficult to believe these effects could completely wipe out a gain of 100! However, the most severe limitation will come from the choice of the test itself. It is therefore important to discuss this test and the assumptions underlying its derivation. This is the purpose of the next section.

One might ask, "Why not use a better test?" The answer to this question is two-fold: if there is one, it is well hidden in the literature, and second it is fairly evident, from experience, that sophistication in statistical techniques reaches rapidly a point of diminishing returns unless paralleled with judicious selection of variables to be tested and a thorough knowledge of the particular local hydrologic conditions. Again this point is justified by the conclusion of the present study.

2.2 Target-control conditional Student's t-test. The goal of weather modification experiments is to increase the runoff in the watershed, and it is logical to postulate the null [12] hypothesis:

H_o: There is no change in mean runoff due to the weather modification experiments. This will be tested against the alternative [12] hypothesis

H_a: There is a change in mean runoff caused by man's weather modification experiments. If the art of weather modification is advanced enough the possibility of a decrease need not be considered and a one-tailed [12] test is implied. If not, a two-tailed [12] test is implied.

The level of significance α which is the probability of rejecting a true hypothesis, will be either 5% or 1%.

The target-control concept uses the relationship existing between the streamflows, from a treated or target watershed, to those from an adjacent and untreated watershed; the latter serving as a control to the previous watershed, since its flows are not affected by the cloud seeding operations. Additional information from the control watershed can be used to discriminate a change in the target watershed behavior. In other words, it makes the target look as though it has an effective coefficient of variation much smaller than its actual one. The larger the coefficient of correlation between target and control the smaller the apparent coefficient of variation of the target. This concept assumes:

(a) The target and control streamflows are highly correlated.

(b) The control watershed is sufficiently far from the target watershed to preclude contamination, but close enough to provide a high correlation.

(c) The target streamflow observations are independent.

With (x) being the series of independent flows for the control and (y) the corresponding series for the target, a bivariate normal distribution is assumed for the joint series (x,y) for the non-seeded period. The seeded period will provide two new sets of observations (ξ) and (η); (ξ) and (η) being the sets of independent flow values, respectively, for the control and the target. It is assumed that the coefficient of correlation ρ between target and control has not changed during the seeded period, and that the joint series (ξ,η) has also a bivariate normal distribution.

When the above conditions are satisfied, any significant difference in streamflow, taking into account the relation between the two watersheds, beyond that associated with a natural variation can be attributed to cloud seeding effects.

Because variances of the target and control variables and their coefficient of correlation are assumed unaffected by seeding, the two regression lines, one for the sample before seeding, one for the sample after seeding, are parallel (see Fig. 1). Then, the null hypothesis is that the two populations have the same regression line, that is, the difference in ordinates at the origin AB is not significantly different from zero. It should be noted that whether or not the control mean has changed under seeded conditions will not affect the test.

The null hypothesis can be formulated in this way: the adjusted means of the two populations, $\overline{y}_{x_o}$ and $\overline{\eta}_{x_o}$ at $x = \xi = x_o$, are equal, whatever the value of x_o. The adjusted means are:

for the non-seeded period, $\overline{y}_{x_o} = \overline{y} - \overline{b}(x-\overline{x})$, and

for the seeded period, $\overline{\eta}_{x_o} = \overline{\eta} - \overline{b}(\xi-\overline{\xi})$.

Where $\overline{b}$ is the weighted average regression coefficient:

$$\overline{b} = \frac{\sum\limits_{i=1}^{N} (x_i-\overline{x})(y_i-\overline{y}) + \sum\limits_{j=1}^{M} (\xi_j-\overline{\xi})(\eta_j-\overline{\eta})}{\sum\limits_{i=1}^{N} (x_i-\overline{x})^2 + \sum\limits_{j=1}^{M} (\xi_j-\overline{\xi})^2} .$$

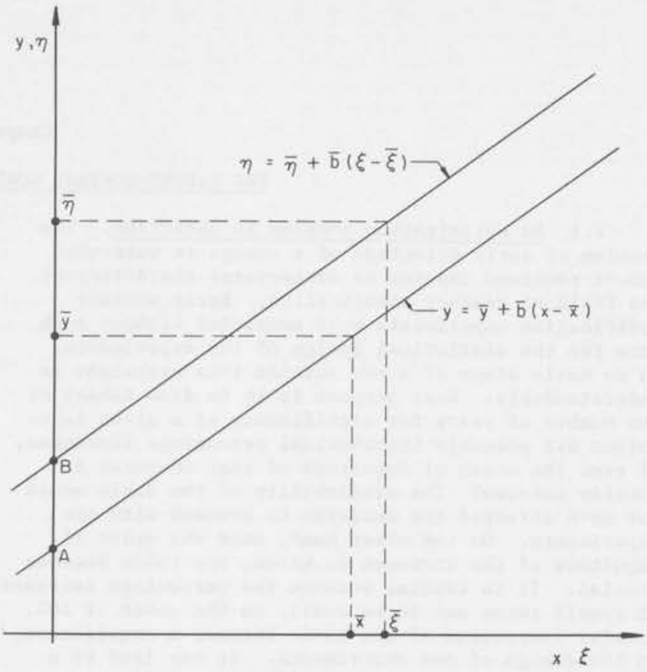


Fig. 1 Target control regression lines before and after seeding operations

The difference AB is:

$$\overline{y}_{x_o} - \overline{\eta}_{x_o} = \overline{y} - \overline{\eta} - \overline{b}(\overline{x}-\overline{\xi}) .$$

AB is a linear combination of three independent observations $\overline{y}$, $\overline{\eta}$, $\overline{b}$ with population means μ_y, μ_η, β and variances $\frac{\sigma^2}{N}$, $\frac{\sigma^2}{M}$, $\frac{\sigma^2}{\sum\limits_{i=1}^{N} (x_i-\overline{x})^2 + \sum\limits_{i=1}^{M} (\xi_i-\overline{\xi})^2}$ respectively. Then AB has a normal distribution with mean $\mu_y - \mu_\eta - \beta(\overline{x}-\overline{\xi})$ and variance

$$\sigma^2 \left[\frac{1}{N} + \frac{1}{M} + \frac{(\overline{x} - \overline{\xi})^2}{\sum\limits_{i=1}^{N} (x_i-\overline{x})^2 + \sum\limits_{i=1}^{M} (\xi_i-\overline{\xi})^2}\right]$$

where σ^2 is the common variance of the arrays.

Under the null hypothesis, $H_o : \mu_y - \mu_\eta = \beta(\overline{x}-\overline{\xi})$, the statistic

$$t_o = \frac{\overline{y} - \overline{\eta} - \overline{b}(\overline{x} - \overline{\xi})}{s\left[\frac{1}{N} + \frac{1}{M} + \frac{(\overline{x} - \overline{\xi})^2}{\sum\limits_{i=1}^{N} (x_i-\overline{x})^2 + \sum\limits_{j=1}^{M} (\xi_j-\overline{\xi})^2}\right]^{\frac{1}{2}}} \qquad (2)$$

where s^2 is the unbiased estimate of the common variance of the arrays:

$$s^2 = (1-r\ ) \frac{\left[\sum_{i=1}^{N} (y_i-\overline{y})^2 + \sum_{j=1}^{M} (\eta_j-\overline{\eta})^2 \right]}{N + M - 3}$$

$$r^2 = \frac{\left[\sum_{i=1}^{N} (x_1-\overline{x})(y_i-\overline{y}) + \sum_{j=1}^{M} (\xi_j-\overline{\xi})(\eta_j-\overline{\eta}) \right]^2}{\left[\sum_{i=1}^{N} (x_i-\overline{x})^2 + \sum_{j=1}^{M} (\xi_j-\overline{\xi})^2 \right] \left[\sum_{i=1}^{N} (y_i-\overline{y})^2 + \sum_{j=1}^{M} (\eta_j-\overline{\eta})^2 \right]}$$

follows Student's t distribution with (N + M - 3) degrees of freedom [13].

On the basis of the data, t_o can be computed; a subroutine has been written for this purpose [14], and it performs a one- or two-tailed test by comparison of t_o with a table of the Student's t distribution as a function of the number of degrees of freedom.

Chapter III

STREAMFLOW DATA USED FOR STUDY

All streamgage stations used in this study are located in the Upper Colorado River Basin within the State of Colorado. The target and control watersheds must satisfy some criteria as closely as possible. These conditions, which form the basis for the selection of the watersheds, are now discussed.

3.1 Physiography and location. The statistical investigation of weather modification attainments as presented in this paper were undertaken in connection with a project of the Bureau of Reclamation, Office of Atmospheric Water Resources. A pilot project to increase winter precipitation over high elevation watersheds in two areas of the Upper Colorado River Basin [15] is to be initiated in 1969.

The watersheds selected for this study are located in the Upper Colorado River Basin and have elevations as near as possible to the 9,000 feet level--a level determined [9] as a requirement to start a nucleation process in cloud seeding experiments. The majority of the selected stations are about 7,000 feet high.

No restriction was imposed on the size of the drainage area. Watersheds of more than 100 square miles are preferred because they are more likely to provide a more representative response to a man-made increase in precipitation.

3.2 Availability of records. A rather sizable number of data is required when working with daily flows; therefore, the computations were handled by the CDC 6400 computer at Colorado State University. Because better and fast processing of data can be done on magnetic tapes, watersheds with available data on these tapes were selected. Selection of thirty-one stations in the Upper Colorado River Basin from a U.S. Geological Survey tape was based on the accuracy of historical records.

3.3 Virginity of the flows and accuracy of the measurements. Most of the rivers of the Colorado River Basin have been subjected at one time or another, to some kind of human intervention, regulation or diversion. For the purpose of detection of an increase due to artificial precipitation, virginity of the flow is strongly required because man-made diversions or regulations by dams often far exceed the range of the expected increase due to cloud seeding and are not often consistent in time and in quantities from year to year.

Streamflows affected by Transmountain Diversions were excluded because such diversions generally involve important quantities of water, and the data required for corrections were not available.

Streamflows with upstream regulation or transbasin diversions were excluded except where the dams causing the regulation are small or the diversions are made for irrigation of very small acreages. Streamflows with intrabasin diversion for irrigation were accepted if the size of the irrigated area was small.

For the spring season the United States Geological Survey considers the accuracy of the discharge measurements as good.

3.4 Correlation target-control. A high correlation between target and control watersheds daily flows is desirable for the purpose of this study. To discriminate among the stations before starting the study of the daily flows, the correlation between target an control was estimated using seasonal flow, i.e., water yield from March to August.

On the basis of these criteria, 10 stations were selected (see Table 2, 3 and 4 and Fig. 2.

Fig. 2 Location of the selected stations in the Upper Colorado River Basin

TABLE 2

DESCRIPTION OF THE STATIONS SELECTED

Identification									
Tape no.	USGS no.	CSU no.	Elevation ft.	Drainage area sq. mi.	Length of record year	Trans-mountain diversion	Upstream regulation	Trans-basin diversion	Intra-basin diversion*
12	9.0825	1592140	6400	225	25	None	None	None	irrig. for 2050 ac.b.
16	9.0975	1425625	6920	139	39	None	None	to irrig. 280 ac.	irrig. for 1300 ac. a.
17	9.1045	1420800	7400	7	20	None	small dam	None	None
18	9.1050	1420000	4800	604	21	None	small dams	None	irrig. for 25000 ac. a.
19	9.1125	1378100	8008	295	38	None	None	None	irrig. for 7400 ac. a.
21	9.1190	1377200	7628	1020	20	None	None	None	irrig. for 24000 ac. a.
22	9.1245	1375400	7827	338	23	None	None	None	irrig. for 24000 ac. a.
25	9.1345	1373020	7160	35	20	None	small dam	None	small irrig. no data
26	9.1435	1371810	6500	39	40	None	small dam	small-no data	small irrig. no data
30	9.1665	1277200	6924	556	48	None	None	None	irrig. 2000 ac. b.

*irrig. means irrigation; ac. a. means acres above station; ac. b. means acres below station.

STATION DESCRIPTIONS

Identification			
Tape no.	USGS no.	CSU no.	Name
12	9.0825	1592140	Crystal River near Redstone, Colorado
16	0.0975	1425625	Buzzard Creek near Collbran, Colorado
17	9.1045	1420800	Mesa Creek near Mesa, Colorado
18	9.1050	1420000	Plateau Creek near Cameo, Colorado
19	9.1125	1378100	East River at Almont, Colorado
21	9.1190	1377200	Tomichi Creek at Gunnison, Colorado
22	9.1245	1375400	Lake Fork at Gateview, Colorado
25	9.1345	1373020	Leroux Creek near Cedaredge, Colorado
26	9.1435	1371810	Surface Creek at Cedaredge, Colorado
30	9.1665	1277200	Dolores River at Dolores, Colorado

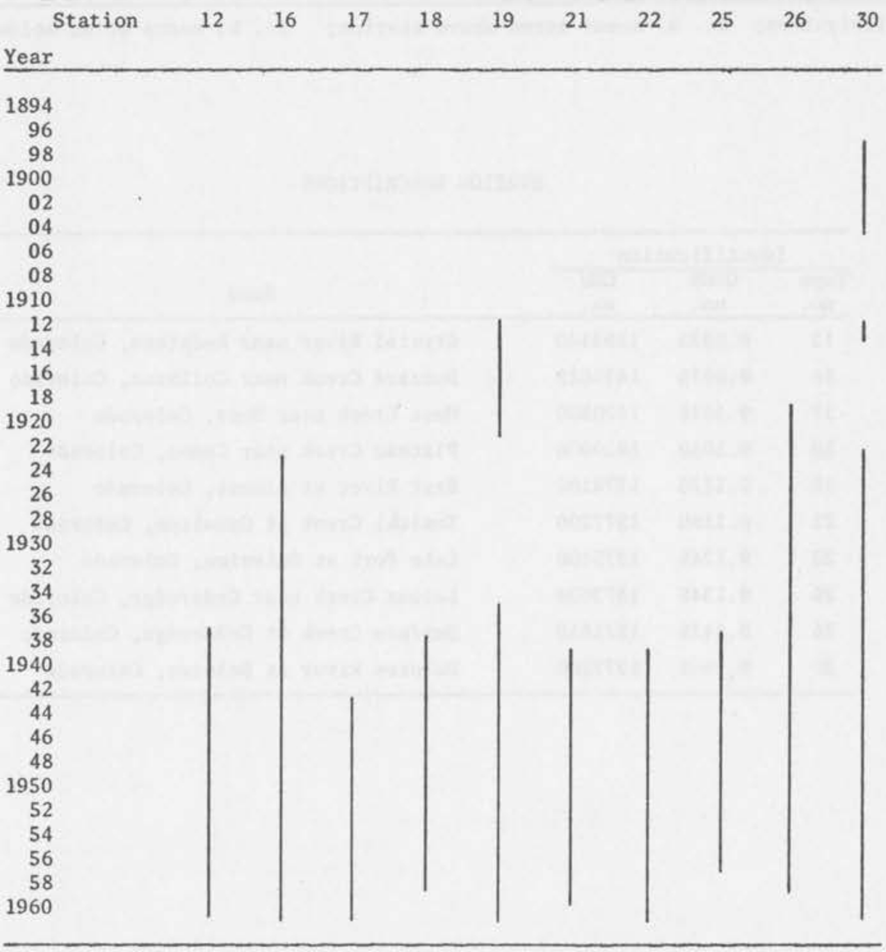
TABLE 3

TARGET-CONTROL CORRELATION ON THE BASIS OF SEASONAL FLOWS

Identification	12	16	17	18	19	21	22	25	26
12									
16	0.771								
17	0.625	0.889							
18	0.728	0.969	0.892						
19	0.94	0.629	0.515	0.618					
21	0.825	0.829	0.715	0.811	0.862				
22	0.807	0.866	0.736	0.832	0.792	0.878			
25	0.88	0.852	0.822	0.838	0.771	0.766	0.795		
26	0.776	0.876	0.836	0.833	0.659	0.765	0.827	0.92	
30	0.785	0.854	0.889	0.877	0.694	0.848	0.914	0.803	0.872

TABLE 4

LENGTH AND AVAILABILITY OF HISTORICAL RECORD FOR DAILY FLOWS



Chapter IV

THE STOCHASTIC STRUCTURE OF DAILY FLOW

4.1 The naive approach. It might be summarily inferred that the use of daily runoff instead of seasonal runoff in the application of the test would only entail a larger amount of data processing. However, this quick extrapolation is erroneous for two reasons:

(1) The daily flow observations for different days of the year come from different statistical populations, and

(2) From day to day the flow values are highly correlated.

For these two reasons the straight application of the test to daily runoff for every day of the season and on face value would violate the assumptions of the derivation of the test and invalidate the results of the test. Assertion (1) is demonstrated in Fig. 3. The expected value $P(t)$, or more rigorously its estimate, $\hat{P}(t)$, of the daily flow, $Q(t)$, varies from one date to another. In this study the time variable t takes only discrete integer values, with $t = 1$ corresponding to the first day of the water year, i.e. October 1st, and $t = 365$ to September 30. For convenience a table of correspondence between calendar dates and values of t is given (Table 5). The sets of Fig. 3 show that the standard deviation also varies considerably from day to day. In these figures, the coefficient of variation (ratio of standard deviation over mean) is also given.

Assertion (2) is also clearly supported in Fig. 4 which shows the autocorrelation values, $r(k)$, for all dates of the year and for various lags.

4.2 Standardization of daily streamflows. To overcome difficulty (1), i.e., the fact that daily flow observations for different dates of the year come from different statistical populations, it is necessary to perform a transformation on the daily flow values. Hopefully the transformed data will belong to the same population. If $Q(t)$ denotes the daily flow for date t, $P(t)$ its expected value, $\hat{P}(t)$ the estimate of $P(t)$, $S(t)$ and $\hat{S}(t)$ the standard deviation and its estimate, then the annual observation of $Q(t)$, $Q_i(t)$ can be standardized by the transformation:

$$q_i(t) = \frac{Q_i(t) - \hat{P}(t)}{\hat{S}(t)} \qquad (3)$$

with i being an index referring to the year,

$$\hat{P}(t) = \frac{1}{n} \sum_{i=1}^{n} Q_i(t) \quad \text{for any given } t,$$

where n is the number of years with available records, and

$$\hat{S}^2(t) = \frac{1}{n-1} \sum_{i=1}^{n} [Q_i(t) - \hat{P}(t)]^2 \text{ for any given } t.$$

The standardized daily runoff variable:

$$q(t) = \frac{Q(t) - \hat{P}(t)}{\hat{S}(t)} \qquad (4)$$

is approximately normal if $Q(t)$ is normally distributed, with expected value approximately zero and variance approximately unity. For the historical period of record the sample estimate of the expected value of $q(t)$ is exactly zero and the estimate of the variance is exactly one, from the very definition of $q(t)$.

To pool together and use the daily flows for different t, as elements of one and the same population, the series must be "stationary." In hydrologic investigation, it is generally considered sufficient to have wide-sense stationarity. Wide-sense stationarity is defined by the following two equations where E[ ] denotes the expected value:

$$E[q(t)] = \text{Constant}$$

$$\text{Cov}[q(t_1)q(t_2)] = C(t_2-t_1): \text{ a function of } (t_2-t_1)=k \text{ only.}$$

From the very definition of $q(t)$ the first condition is met and the second condition is met for $t_1 = t_2$. It remains to verify that the second condition is met for various lag values. The dependence of a given day t_1 with another day t_2 can be measured by the correlation coefficient r, computed over the two samples of n elements of the populations of the daily flow for these two given days:

$$\hat{r}(k) = \frac{\hat{C}\text{ov}[q(t_1),q(t_2)]}{\left[\hat{V}\text{ar}[q(t_1)]\hat{V}\text{ar}[q(t_2)]\right]^{\frac{1}{2}}}$$

with $k = (t_2-t_1)$.

By the nature of the standardization procedure this expression reduces [16] to the simpler form:

$$\hat{r}(k) = \frac{1}{n} \sum_{i=1}^{n} q_i(t_1)q_i(t_2) . \qquad (5)$$

The computation of $r(k)$ was performed for different values of t_2 and k; t_2 varying from 1 to 365 and k from 1 to 37. Analysis of the results points to the following:

(a) For a given value of k, $r(k)$ varies significantly for different t_2, that is, from day to day, and the assumption, $r(k)$ depends only on $k = t_2-t_1$, cannot be considered as valid throughout the whole year. In other words, the standardization did not yield stationarity in the wide sense.

(b) For a given day (t_2), $r(k)$ decreases and tends toward zero, as k increases.

However, it is possible to consider that the coefficient of correlation, depends only on k for some period of the year (see Fig. 4). This period is the spring season, more precisely it extends from March to June.

For the spring season it is legitimate to consider that the conditions of stationarity in the wide sense are met. It is then possible to consider, as is usually done [17], that the mathematical expectation of both $q(t_1)$ and $q(t_1)q(t_2)$--obtained by averaging over an ensemble of realizations of the time series--can be replaced by the time averages of the same quantities over one realization. The advantage of this procedure is to permit the use of a sample of larger size. Proper application also requires that correlation between ordinates of the random function $q(t)$, taken at different instants of time, should decrease with sufficient rapidity, since it is only in this case that one realization with respect to time can be approximately considered as a set of several independent realizations, and that the difference between means obtained by these two methods vanish. This latter condition is accepted on the basis of the results found for $r(k)$.

The serial correlation coefficient $R_i(k)$ for a given realization i, that is for a given year i can be computed. Again by the nature of the standardization procedure [16] the expression is simple:

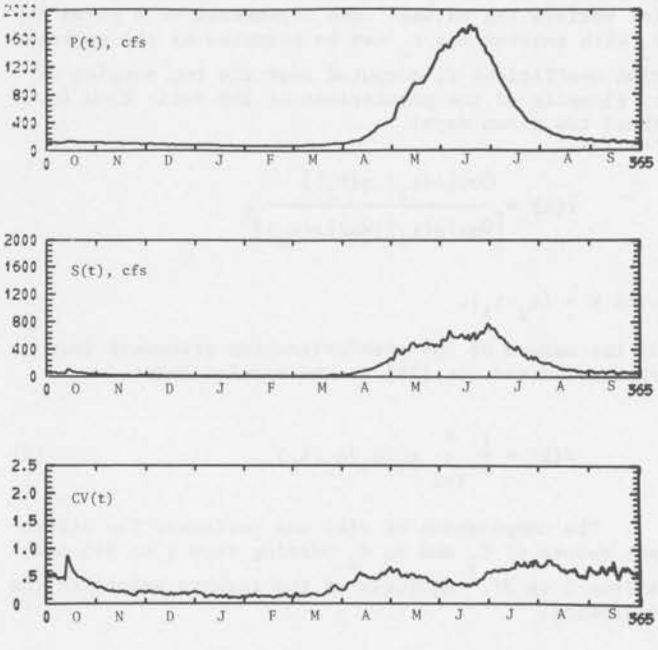
$$R_i(k) = \frac{1}{\beta-\alpha} \sum_{t=\alpha}^{\beta} q_i(t)\, q_i(t-k) \qquad (6)$$

In eq. (6) α and β are the indexes of the days which respectively begin and end the considered spring period. For a station with n years of historical records, n values for $R(k)$ can be computed for every value of k. If all the realizations have been obtained under identical conditions, it is suggested [18] that each of them should be analyzed by the method indicated above. Then the estimated values of the mathematical expectations and correlation functions should be averaged over all the realizations.

The average of the $R_i(k)$ over all realizations i is:

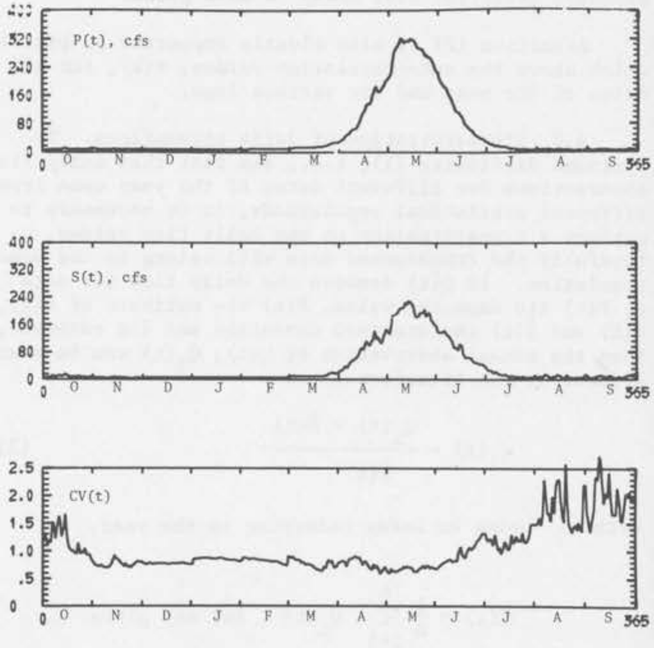
$$\overline{R}(k) = \frac{1}{n} \sum_{i=1}^{n} R_i(k) \; . \qquad (7)$$

Based on the correlograms, i.e., graphs of $\overline{R}(k)$ versus k, it is possible to determine a minimum lag beyond which the standardized daily flows can be considered as independent. The resulting series of spaced standardized daily flows then satisfies the conditions of applicability of the target-control test.



Characteristics of the daily flow random function Q(t), for Station 12 -- Crystal River near Redstone, Colorado

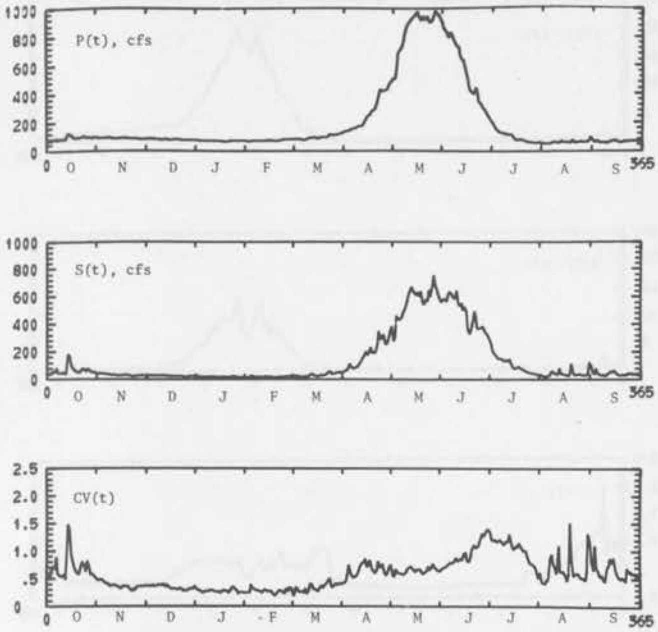
P(t): Expectation of Q(t)
S(t): Standard deviation of Q(t)
CV(t): Coefficient of variation of Q(t)



Characteristics of the daily flow random function Q(t), for Station 16 -- Buzzard Creek near Collbran, Colorado

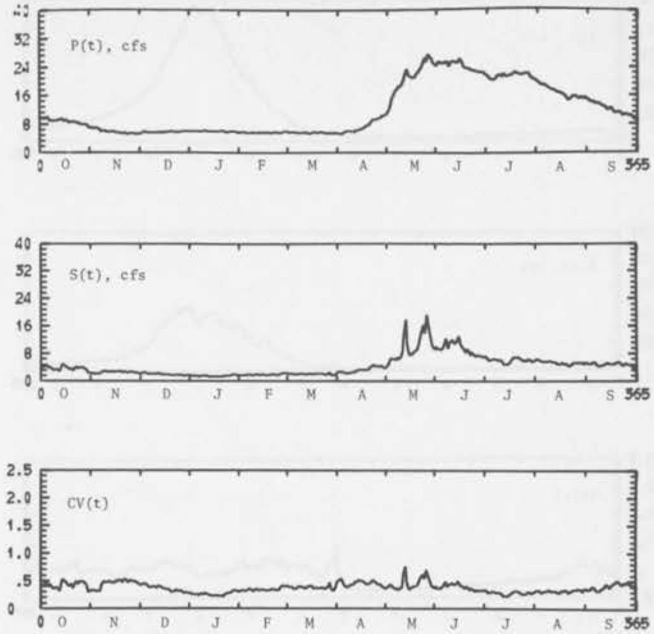
P(t): Expectation of Q(t)
S(t): Standard deviation of Q(t)
CV(t): Coefficient of variation of Q(t)

Figure 3



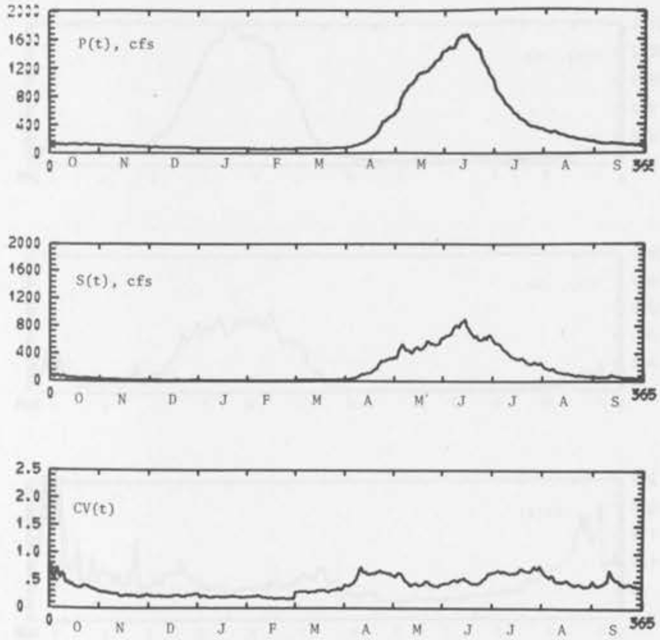
Characteristics of the daily flow random function Q(t), for Station 17 -- Mesa Creek near Mesa, Colorado

P(t): Expectation of Q(t)
S(t): Standard deviation of Q(t)
CV(t): Coefficient of variation of Q(t)



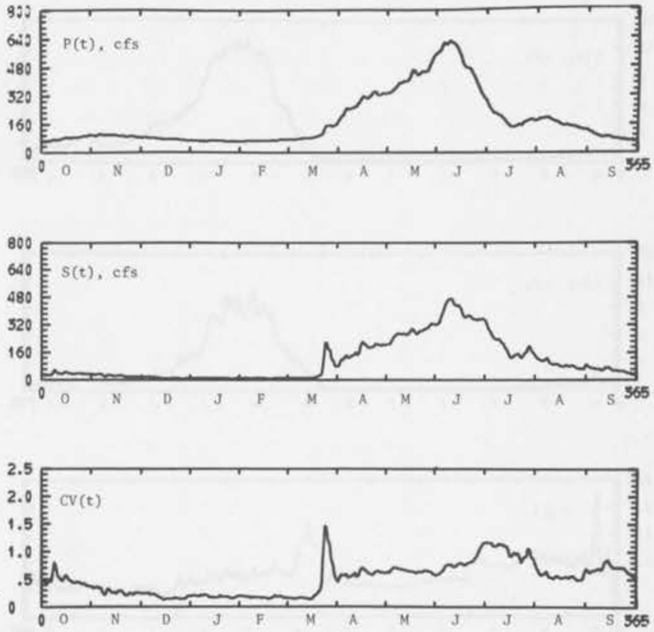
Characteristics of the daily flow random function Q(t), for Station 18 -- Plateau Creek near Cameo, Colorado

P(t): Expectation of Q(t)
S(t): Standard deviation of Q(t)
CV(t): Coefficient of variation of Q(t)



Characteristics of the daily flow random function Q(t), for Station 19 -- East River at Almont, Colorado

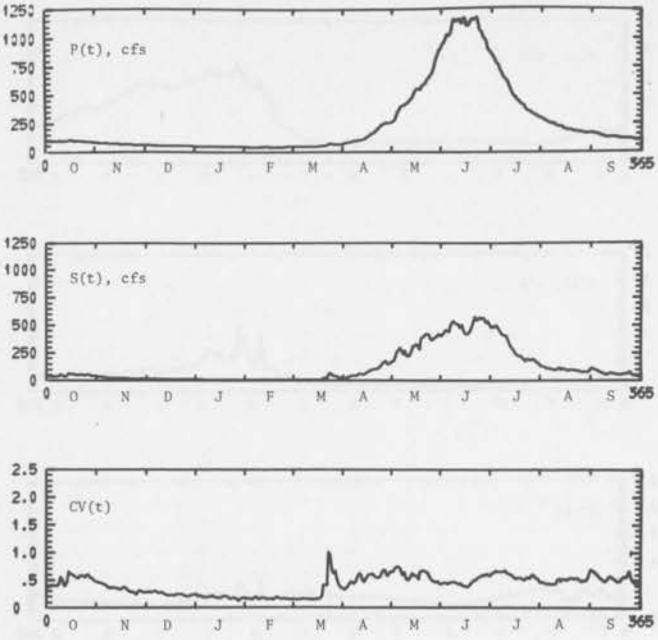
P(t): Expectation of Q(t)
S(t): Standard deviation of Q(t)
CV(t): Coefficient of variation of Q(t)



Characteristics of the daily flow random function Q(t) for Station 21 -- Tomichi Creek at Gunnison, Colorado

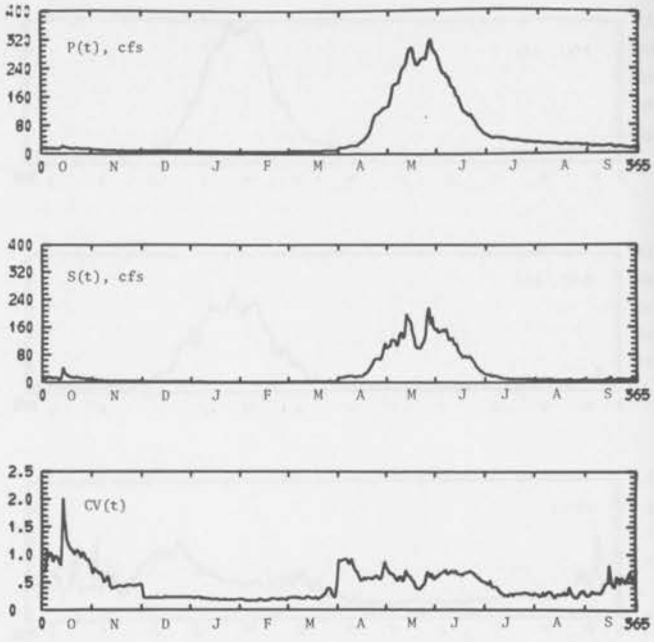
P(t): Expectation of Q(t)
S(t): Standard deviation of Q(t)
CV(t): Coefficient of variation of Q(t)

Figure 3 (continued)



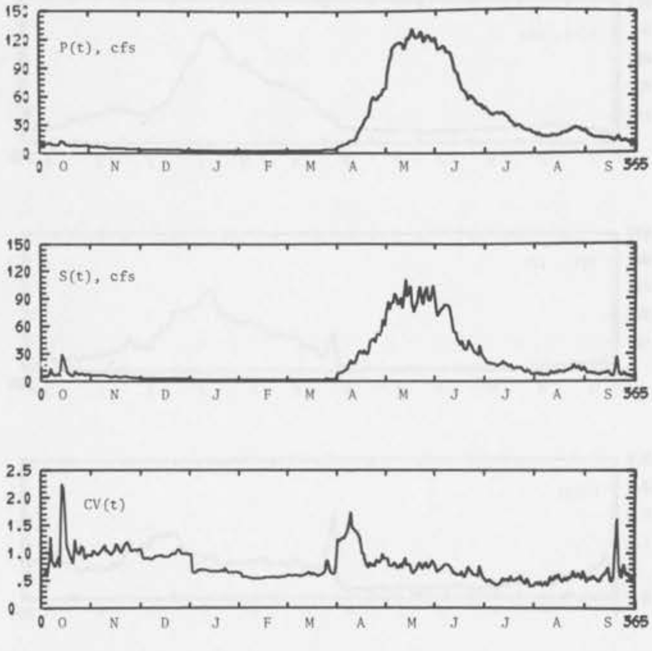
Characteristics of the daily flow random function Q(t), for Station 22 -- Lake Fork at Gateview, Colorado

P(t): Expectation of Q(t)
S(t): Standard deviation of Q(t)
CV(t): Coefficient of variation of Q(t)



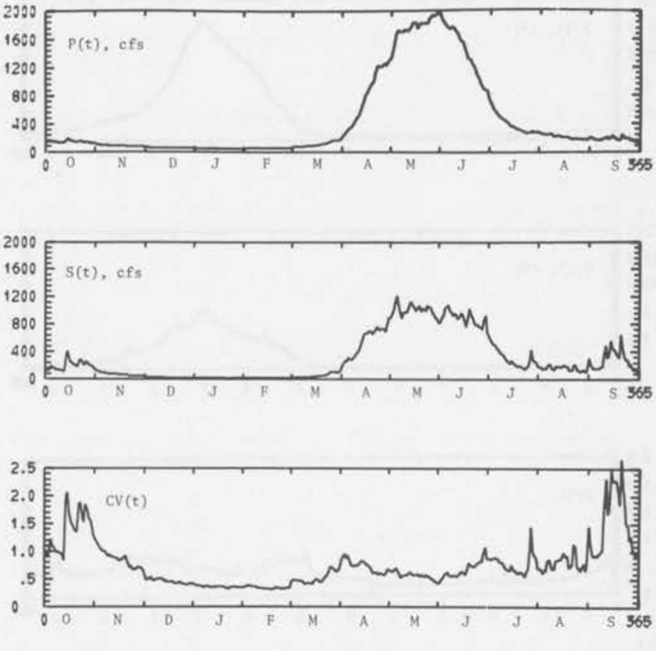
Characteristics of the daily flow random function Q(t), for Station 25 -- Leroux Creek near Cedaredge, Colorado

P(t): Expectation of Q(t)
S(t): Standard deviation of Q(t)
CV(t): Coefficient of variation of Q(t)



Characteristics of the daily flow random function Q(t), for Station 26 -- Surface Creek at Cedaredge, Colorado

P(t): Expectation of Q(t)
S(t): Standard deviation of Q(t)
CV(t): Coefficient of variation of Q(t)



Characteristics of the daily flow random function Q(t), for Station 30 --Dolores River at Dolores, Colorado

P(t): Expectation of Q(t)
S(t): Standard deviation of Q(t)
CV(t): Coefficient of variation of Q(t)

Figure 3 (continued)

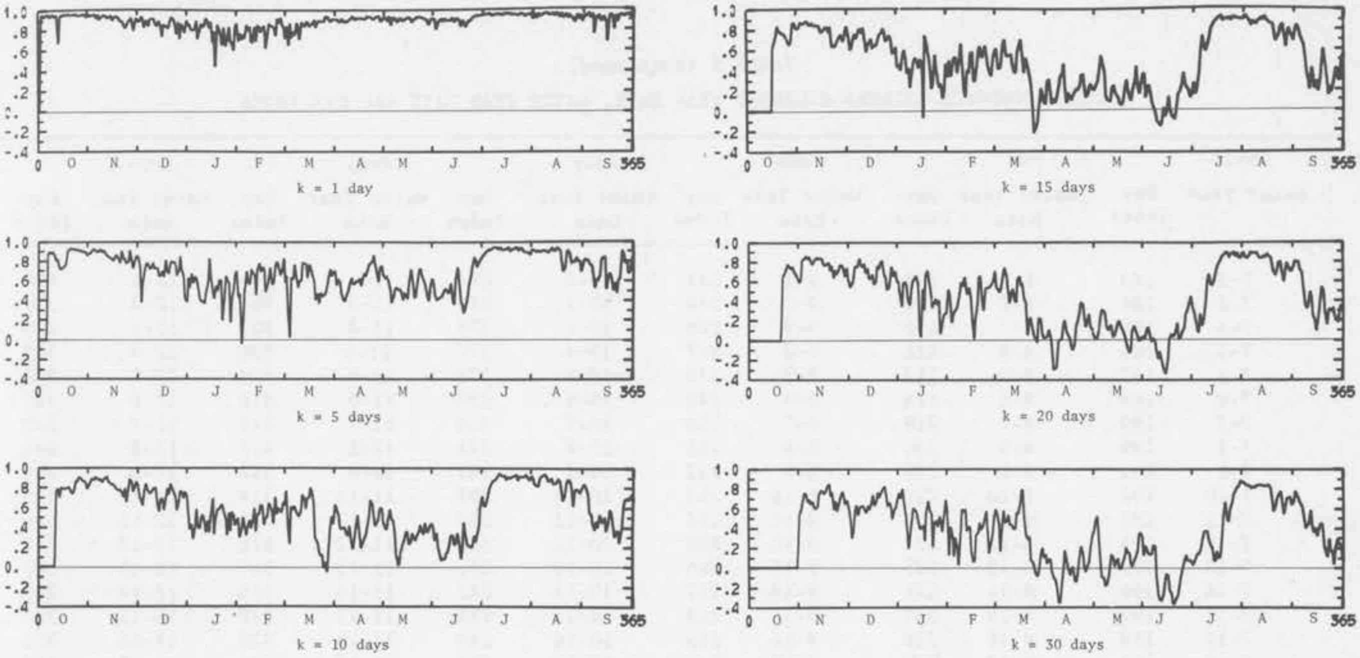


Figure 4 An illustration of r(k) versus time for Station 12 and different values of k

-r(k) has not been computed and has been set up equal to zero for the first k days of the water year

TABLE 5

CORRESPONDENCE BETWEEN CALENDAR YEAR DATE, WATER YEAR DATE AND DAY INDEX

Oct.		Nov.		Dec.		Jan.		Feb.		MARCH	
Water Year Date	Day Index	Water Year Date	Day Index	Water Year Date	Day Index	Water Year Date	Day Index	Water Year Date	Day Index	Water Year Date	Day Index
1-1	1	2-1	32	3-1	62	4-1	93	5-1	124	6-1	152
1-2	2	2-2	33	3-2	63	4-2	94	5-2	125	6-2	153
1-3	3	2-3	34	3-3	64	4-3	95	5-3	126	6-3	154
1-4	4	2-4	35	3-4	65	4-4	96	5-4	127	6-4	155
1-5	5	2-5	36	3-5	66	4-5	97	5-5	128	6-5	156
1-6	6	2-6	37	3-6	67	4-6	98	5-6	129	6-6	157
1-7	7	2-7	38	3-7	68	4-7	99	5-7	130	6-7	158
1-8	8	2-8	39	3-8	69	4-8	100	5-8	131	6-8	159
1-9	9	2-9	40	3-9	70	4-9	101	5-9	132	6-9	160
1-10	10	2-10	41	3-10	71	4-10	102	5-10	133	6-10	161
1-11	11	2-11	42	3-11	72	4-11	103	5-11	134	6-11	162
1-12	12	2-12	43	3-12	73	4-12	104	5-12	135	6-12	163
1-13	13	2-13	44	3-13	74	4-13	105	5-13	136	6-13	164
1-14	14	2-14	45	3-14	75	4-14	106	5-14	137	6-14	165
1-15	15	2-15	46	3-15	76	4-15	107	5-15	138	6-15	166
1-16	16	2-16	47	3-16	77	4-16	108	5-16	139	6-16	167
1-17	17	2-17	48	3-17	78	4-17	109	5-17	140	6-17	168
1-18	18	2-18	49	3-18	79	4-18	110	5-18	141	6-18	169
1-19	19	2-19	50	3-19	80	4-19	111	5-19	142	6-19	170
1-20	20	2-20	51	3-20	81	4-20	112	5-20	143	6-20	171
1-21	21	2-21	52	3-21	82	4-21	113	5-21	144	6-21	172
1-22	22	2-22	53	3-22	83	4-22	114	5-22	145	6-22	173
1-23	23	2-23	54	3-23	84	4-23	115	5-23	146	6-23	174
1-24	24	2-24	55	3-24	85	4-24	116	5-24	147	6-24	175
1-25	25	2-25	56	3-25	86	4-25	117	5-25	148	6-25	176
1-26	26	2-26	57	3-26	87	4-26	118	5-26	149	6-26	177
1-27	27	2-27	58	3-27	88	4-27	119	5-27	150	6-27	178
1-28	28	2-28	59	3-28	89	4-28	120	5-28	151	6-28	179
1-29	29	2-29	60	3-29	90	4-29	121	5-29	---	6-29	180
1-30	30	2-30	61	3-30	91	4-30	122	5-30	---	6-30	181
1-31	31	2-31	--	3-31	92	4-31	123	5-31	---	6-31	182

TABLE 5 (continued)

CORRESPONDENCE BETWEEN CALENDAR YEAR DATE, WATER YEAR DATE AND DAY INDEX

April		May		June		July		Aug.		Sept.	
Water Year	Day Index	Water Year Date	Day Index	Water Year Date	Day Index	Water Year Date	Day Index	Water Year Date	Day Index	Water Year Date	Day Index
7-1	183	8-1	213	9-1	244	10-1	274	11-1	305	12-1	336
7-2	184	8-2	214	9-2	245	10-2	275	11-2	306	12-2	337
7-3	185	8-3	215	9-3	246	10-3	276	11-3	307	12-3	338
7-4	186	8-4	216	9-4	247	10-4	277	11-4	308	12-4	339
7-5	187	8-5	217	9-5	248	10-5	278	11-5	309	12-5	340
7-6	188	8-6	218	9-6	249	10-6	279	11-6	310	12-6	341
7-7	189	8-7	219	9-7	250	10-7	280	11-7	311	12-7	342
7-8	190	8-8	220	9-8	251	10-8	281	11-8	312	12-8	343
7-9	191	8-9	221	9-9	252	10-9	282	11-9	313	12-9	344
7-10	192	8-10	222	9-10	253	10-10	283	11-10	314	12-10	345
7-11	193	8-11	223	9-11	254	10-11	284	11-11	315	12-11	346
7-12	194	8-12	224	9-12	255	10-12	285	11-12	316	12-12	347
7-13	195	8-13	225	9-13	256	10-13	286	11-13	317	12-13	348
7-14	196	8-14	226	9-14	257	10-14	287	11-14	318	12-14	349
7-15	197	8-15	227	9-15	258	10-15	288	11-15	319	12-15	350
7-16	198	8-16	228	9-16	259	10-16	289	11-16	320	12-16	351
7-17	199	8-17	229	9-17	260	10-17	290	11-17	321	12-17	352
7-18	200	8-18	230	9-18	261	10-18	291	11-18	322	12-18	353
7-19	201	8-19	231	9-19	262	10-19	292	11-19	323	12-19	354
7-20	202	8-20	232	9-20	263	10-20	293	11-20	324	12-20	355
7-21	203	8-21	233	9-21	264	10-21	294	11-21	325	12-21	356
7-22	204	8-22	234	9-22	265	10-22	295	11-22	326	12-22	357
7-23	205	8-23	235	9-23	266	10-23	296	11-23	327	12-23	358
7-24	206	8-24	236	9-24	267	10-24	297	11-24	328	12-24	359
7-25	207	8-25	237	9-25	268	10-25	298	11-25	329	12-25	360
7-26	208	8-26	238	9-26	269	10-26	299	11-26	330	12-26	361
7-27	209	8-27	239	9-27	270	10-27	300	11-27	331	12-27	362
7-28	210	8-28	240	9-28	271	10-28	301	11-28	332	12-28	363
7-29	211	8-29	241	9-29	272	10-29	302	11-29	333	12-29	364
7-30	212	8-30	242	9-30	273	10-30	303	11-30	334	12-30	365
7-31	---	8-31	243	9-31	---	10-31	304	11-31	335	-----	---

Chapter V

DATA PROCESSING AND ANALYSIS

The statistical techniques described in Chapter IV will be applied to the 10 watersheds selected in Chapter III.

5.1 Characteristics of the daily flow time series. The mean $\hat{P}(t)$ and the standard deviation $\hat{S}(t)$ for a given day (t) were computed for every day and for every station. Sets in Fig. 3 show the results for $\hat{P}(t)$ and $\hat{S}(t)$ plotted as a function of t for each station. All the watersheds have hydrographs very similar in shape. They show a rise in $\hat{P}(t)$ and $\hat{S}(t)$ during the spring season corresponding to the snowmelt with a decline beginning in June and ending in August which leads to a slowly decreasing or steady flow of small amplitude for the winter season. It corresponds to the time when the watershed is covered with snow and the stream is ice-packed. The coefficients of variation for a given day $C_v(t) = \dfrac{\hat{S}(t)}{\hat{P}(t)}$ were computed and plotted against t. They show a period of low values from January to June which coincides with the rising limb of the hydrograph. This period of the rising limb, which for other reasons will be selected as the period of study, is also the period with relatively smaller C_v. This constitutes a definite advantage for the purpose of detection.

5.2 Autocorrelation analysis. The autocorrelation $r(k)$ for the 10 stations was computed for every day and for different values of k varying from 1 to 37. The results are shown on Figs. 4 and 5 for stations 12 and 30.

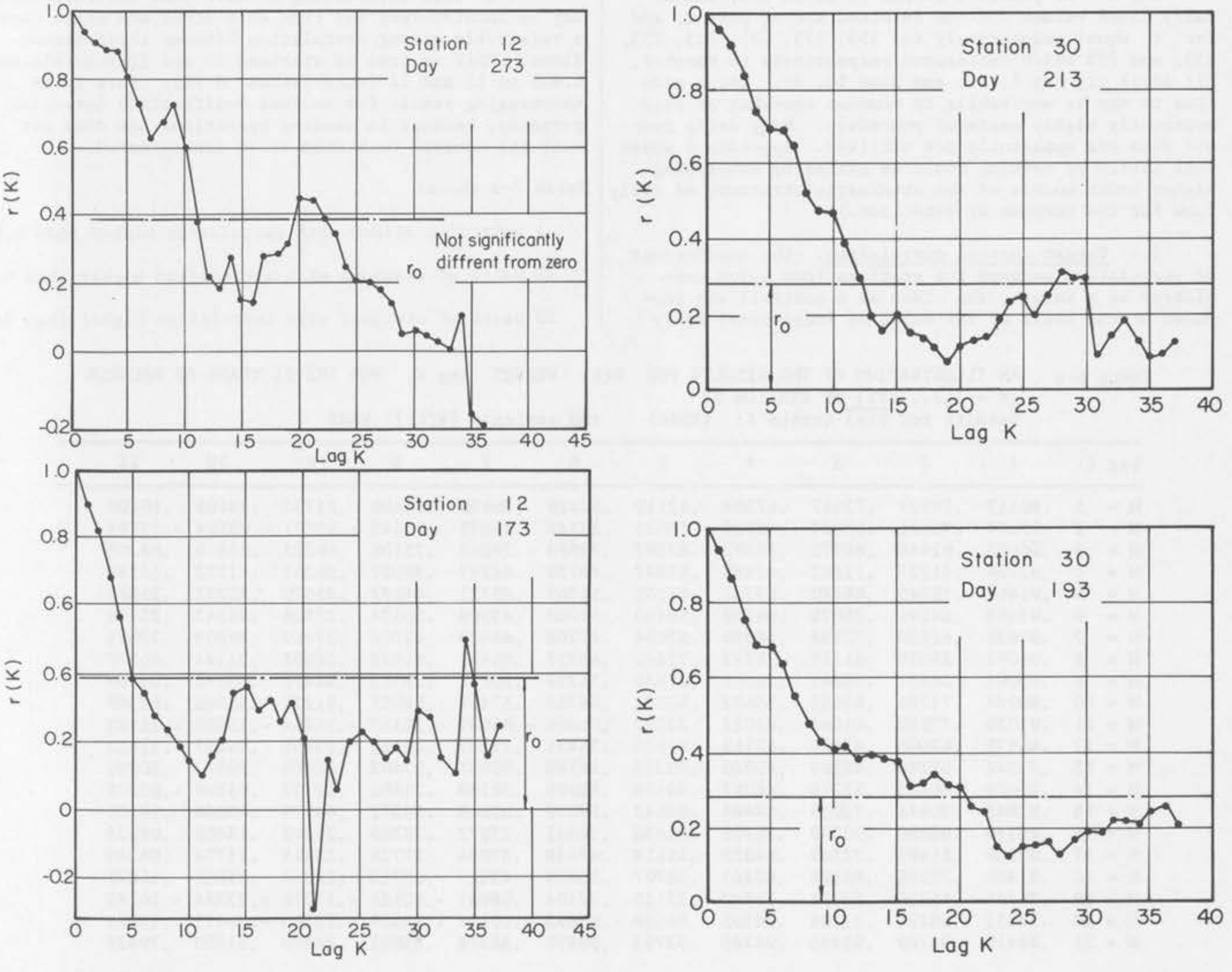


Figure 5 An illustration of r(k) versus k, for a given day and at a given station

Figure 4 shows that r(k) tends to be independent of the days t for the period: March 19th (t = 170) to June 30th (t = 273).

On the basis of this new period, during which the conditions of stationarity are satisfied R(k) was computed for every year (the results of this computation are shown for Station 18 in Table 6-a) then its mean $\overline{R(k)}$ and its variance var [R(k)] (see Table 6-b). This was done for k varying from 1 to 34 by using the formulas described in Chapter IV, where $\alpha = 170$ and $\beta = 273$. Sets in Fig. 6 show the plot of $\overline{R(k)}$ versus k.

An attempt to verify the assumption that consecutive years are independent was made by computing the correlation coefficient between two consecutive years, each day being paired with the same day for the following year, that is, R(k) was computed over two years with k = 365. It showed insignificant correlation.

5.3 Selection of a sequence of independent daily flows. On the basis of the various sets in Fig. 6, a lag common to the 10 stations was selected: K = 20 days. For this lag $\overline{R}(k)$ is considered as nonsignificantly different from zero.

Lag K = 20 yields a sample of seven independent daily flows values for the selected spring period, and for t equal respectively to: 153, 173, 193, 213, 233, 253, and 273 which correspond respectively to March 2, 22; April 11; May 1, 20; and June 10, 30. (As a side line it may be worthwhile to comment somewhat on this apparently highly wasteful procedure. Many daily runoff data are apparently not utilized. Appendix 1 shows that little or nothing would be gained by developing higher order models of the stochastic structure of daily flow for the purpose of detection.)

5.4 Target control correlation. The coefficient of correlation between the stations (one being considered as a target, the other as a control) was computed on the basis of the selected independent daily flow series (Table 7). It was also calculated with other independent daily flow series corresponding to the day-index:

t = 150, 170, 190, 210, 230, 250, 270

that is, for seven days each year corresponding to the dates: February 27; March 19; April 8, 28; May 18; June 7, 27.

As expected, the coefficients of correlation computed in these two manners were not found significantly different. These results are summarized in Table 7.

The results show that the correlations target-control computed with the daily sequences are consistently lower than those computed with the seasonal flows (see Table 3). This is natural because, as the time interval over which the flow is averaged becomes shorter, the watersheds must have very close behaviors to be correlated. In other words, the seasonal flows of two rivers may be correlated, not because the behavior or the patterns of their daily streamflows are exactly the same, but because compensations occur throughout the season, which make their seasonal flows vary in the same way.

It is also interesting to note that two watersheds may be located very far from each other and still have a relatively strong correlation between their streamflows. This is true of stations 30 and 18 (correlation: 0.80) or 12 and 22 (correlation: 0.73). This is an encouraging result for weather modification detection purposes, because in seeding operations one does not want the control watershed to be contaminated.

Table 7-a shows:

1 pair of stations with correlation higher than 0.8.

10 pairs of stations with correlation higher than 0.7.

25 pairs of stations with correlation higher than 0.6.

TABLE 6-a **AN ILLUSTRATION OF THE RESULTS FOR R(k) VERSUS lag K, FOR THE 21 YEARS OF RECORDS (M = 1,2,...21) OF STATION 18**
Results for $\overline{R(k)}$ versus K: (RBAR) **and variance [R(k)]: VARR**

Lag K:	1	2	3	4	5	6	7	8	9	10	11
M = 1	.89117	.79937	.72617	.67208	.62119	.52429	.39939	.32450	.23784	.18869	.10400
M = 2	.90524	.75891	.61607	.49990	.38523	.26144	.14073	.03643	-.03271	-.09594	-.11508
M = 3	.96603	.91948	.88975	.86393	.82367	.78994	.76262	.73106	.69323	.61876	.54268
M = 4	.92754	.81227	.71462	.62888	.55847	.49730	.44267	.39597	.36363	.31572	.24389
M = 5	.91464	.78240	.68440	.63731	.61105	.55869	.49321	.44984	.41670	.35221	.25898
M = 6	.93453	.84195	.75075	.66109	.59460	.51760	.43596	.36974	.32826	.28143	.23170
M = 7	.90636	.81200	.72884	.66020	.57004	.47908	.44629	.42808	.37459	.29908	.22691
M = 8	.96002	.88670	.81319	.75222	.71446	.68337	.65451	.61628	.56563	.51144	.46377
M = 9	.80001	.54861	.38941	.26301	.27640	.33259	.30671	.29953	.34472	.33942	.30106
M = 10	.89944	.74780	.62635	.55672	.55071	.56733	.57457	.54087	.51272	.51965	.52369
M = 11	.91035	.77985	.61044	.41922	.23392	.06886	-.05557	-.12137	-.15254	-.15905	-.13583
M = 12	.85875	.63606	.47568	.42163	.41935	.36431	.28297	.23562	.23465	.25437	.22512
M = 13	.81742	.57140	.48592	.45930	.40385	.34745	.30957	.27403	.26608	.29073	.30285
M = 14	.85671	.66483	.53293	.48257	.46408	.42905	.30189	.21606	.12727	.05396	-.02975
M = 15	.91943	.80444	.72939	.67484	.63542	.59070	.53643	.50372	.44925	.40649	.39105
M = 16	.88110	.68996	.50379	.35706	.26836	.24631	.27572	.28289	.25899	.18409	.08928
M = 17	.92126	.81891	.72869	.64028	.55918	.47548	.37984	.27726	.19115	.11774	.06340
M = 18	.91409	.79255	.69596	.62263	.58797	.53088	.43827	.33713	.22244	.15960	.15279
M = 19	.76101	.46935	.32371	.30880	.32115	.22494	.08901	-.02586	-.13716	-.23384	-.26185
M = 20	.74451	.38231	.11296	.04305	.05559	.05693	-.05124	-.18334	-.22566	-.20471	-.12980
M = 21	.98410	.96769	.95483	.94240	.92753	.90870	.88378	.85961	.84390	.81300	.79428
RBAR	.88922	.73747	.62352	.55082	.50392	.45025	.38321	.32610	.28014	.23871	.20205
VARR	.00401	.02160	.03814	.04297	.04219	.04529	.05600	.06693	.07239	.07219	.06696

TABLE 6-a (continued) AN ILLUSTRATION OF THE RESULTS FOR R(k) VERSUS lag K, FOR THE 21 YEARS OF RECORDS

Lag K:	12	13	14	15	16	17	18	19	20	21	22
M = 1	.02636	-.05298	-.11246	-.17555	-.21631	-.23673	-.21471	-.19177	-.17608	-.17118	-.14743
M = 2	-.14165	-.14931	-.12890	-.11556	-.08837	-.11351	-.15021	-.20035	-.22111	-.24113	-.24307
M = 3	.47701	.42241	.37246	.32038	.27593	.23933	.19057	.13539	.09473	.04852	.01030
M = 4	.17563	.11741	.07364	.06429	.06240	.04710	.04054	.05385	.04356	.00609	-.03149
M = 5	.16670	.11052	.07568	.03918	-.02344	-.08523	-.13617	-.17762	-.19595	-.20260	-.22377
M = 6	.17652	.10547	.02440	-.05971	-.14344	-.20901	-.28521	-.34905	-.41825	-.46985	-.50766
M = 7	.19218	.18114	.14147	.15510	.17573	.16488	.17566	.21600	.29016	.33224	.32103
M = 8	.42606	.40258	.39406	.39494	.38655	.35984	.31645	.27330	.23205	.21114	.21862
M = 9	.20128	.08378	.02543	.03021	.04309	.12469	.13488	.05396	.01611	-.02520	-.06084
M = 10	.50572	.47316	.41388	.38973	.39202	.40856	.40925	.40038	.39872	.40453	.43267
M = 11	-.11441	-.11157	-.11898	-.14492	-.16614	-.18693	-.22743	-.28529	-.34666	-.40023	-.44431
M = 12	.19880	.16743	.16700	.17591	.16386	.11321	.06829	.05003	.01593	-.01936	-.10552
M = 13	.35424	.37794	.34807	.26382	.20896	.18745	.22802	.28359	.28647	.27704	.30786
M = 14	-.08456	-.10815	-.07705	-.12534	-.17395	-.25583	-.27164	-.25830	-.23933	-.33090	-.36186
M = 15	.36108	.31680	.27877	.22587	.17981	.13642	.12044	.14705	.11530	.08606	.06845
M = 16	-.02538	-.11167	-.14545	-.14284	-.10607	-.05761	-.01444	.00593	-.02569	.03110	-.04483
M = 17	-.00086	-.05334	-.10133	-.15232	-.17031	-.18037	-.18620	-.20469	-.23685	-.25430	-.24794
M = 18	.16564	.16915	.13147	.05379	.02938	.02810	.04217	.06041	.06555	.02513	-.02745
M = 19	-.25736	-.28230	-.33315	-.37137	-.33717	-.28183	-.22606	-.17636	-.17232	-.15776	-.11343
M = 20	-.06783	-.03726	-.04060	.00874	.06611	.07374	.04236	.07578	.22489	.38648	.39604
M = 21	.77954	.75292	.73226	.71325	.70172	.66523	.64098	.61830	.58369	.54479	.49254
RBAR	.16737	.13210	.10099	.07370	.06002	.04483	.03322	.02526	.01839	.00384	-.01059
VARR	.06434	.06436	.06286	.06282	.06141	.06036	.05986	.06200	.06747	.07811	.08223

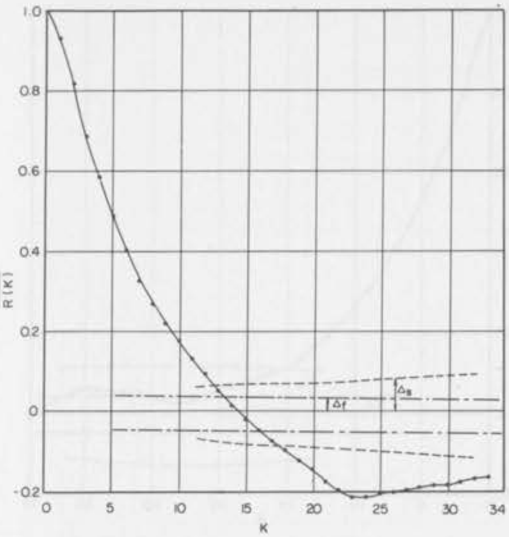
Lag K:	23	24	25	26	27	28	29	30	31	32	33	34
M = 1	-.10804	-.03683	-.02529	-.02356	-.02903	-.00436	.05969	.10778	.09356	.08006	.08370	.13270
M = 2	-.23624	-.19732	-.15065	-.13812	-.11788	-.09185	-.05961	-.01285	.05163	.12691	.20808	.26414
M = 3	-.01373	-.06279	-.10501	-.12037	-.13134	-.14957	-.17320	-.18814	-.20201	-.18903	-.16157	-.13156
M = 4	-.04119	-.02889	.01508	.07105	.11318	.13426	.14864	.12587	.04194	-.06188	-.15377	-.20057
M = 5	-.24257	-.28319	-.30709	-.27957	-.23696	-.22582	-.21834	-.20415	-.20454	-.20017	-.18905	-.18414
M = 6	-.53902	-.55129	-.55726	-.56453	-.56082	-.54343	-.51790	-.48057	-.45860	-.44648	-.41193	-.35784
M = 7	.34637	.42083	.48157	.47979	.46805	.48627	.47310	.41858	.30785	.24187	.22661	.22485
M = 8	.23459	.24496	.24556	.22116	.18515	.15648	.14418	.14746	.13393	.11851	.08649	.04930
M = 9	-.03173	-.01543	-.03343	-.09158	-.14039	-.19874	-.21377	-.17641	-.18764	-.18630	-.18250	-.16438
M = 10	.48194	.52955	.54831	.51110	.45794	.42513	.35282	.29284	.23573	.17705	.13359	.09802
M = 11	-.45682	-.47145	-.48069	-.45452	-.41760	-.37217	-.29981	-.22825	-.14346	-.07513	-.03699	-.00065
M = 12	-.15797	-.14357	-.06249	-.01775	-.03768	-.03846	-.05177	-.07547	-.09943	-.11423	-.12765	-.13546
M = 13	.27334	.21477	.18601	.12114	.10019	.06256	.00965	-.05939	.01626	.09864	.07083	.03877
M = 14	-.39652	-.37531	-.37206	-.41332	-.43387	-.37049	-.36523	-.32191	-.29357	-.23012	-.12634	-.01203
M = 15	.02032	.02047	.05243	.03950	.05149	.06863	.03259	.01678	.00255	-.03061	-.05424	-.12832
M = 16	.05825	.08370	.10762	.12920	.15651	.17173	.17819	.16264	.13891	.10123	.07441	.05590
M = 17	-.24362	-.23663	-.24090	-.24043	-.19223	-.14693	-.11568	-.13541	-.15880	-.18174	-.19746	-.21038
M = 18	-.06450	-.06133	-.03507	-.01071	.01300	-.03005	-.07322	-.08353	-.07979	-.10426	-.10644	-.13817
M = 19	-.06926	-.04528	-.00376	.03137	.12070	.21749	.32157	.41385	.43651	.39275	.38123	.36663
M = 20	.24779	.05905	-.03367	-.07535	-.07208	-.05850	-.03879	.04298	.03439	-.05870	-.14157	-.16265
M = 21	.42125	.31482	.24370	.17144	.08468	.00269	-.07125	-.11816	-.17381	-.20034	-.23270	-.24164
RBAR	-.02464	-.02958	-.02510	-.03115	-.02948	-.02405	-.02369	-.01693	-.02445	-.03533	-.04082	-.03988
VARR	.07954	.07651	.07812	.07345	.06726	.06264	.05829	.05238	.04434	.03741	.03487	.03426

TABLE 6-b

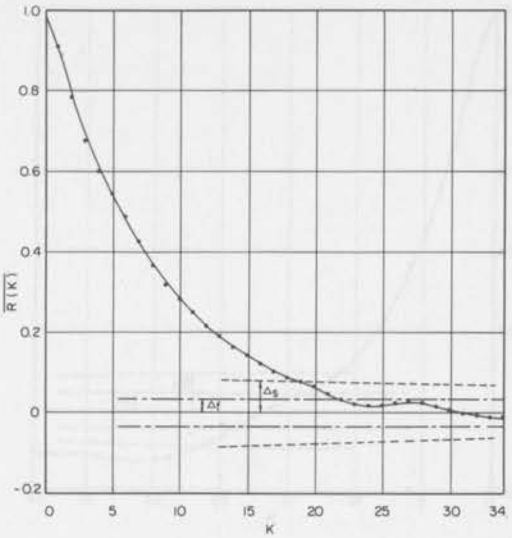
AUTOCORRELATION R(k)

Values of its Mean $\overline{R(k)}$ and of its Variance Var [R(k)] versus k

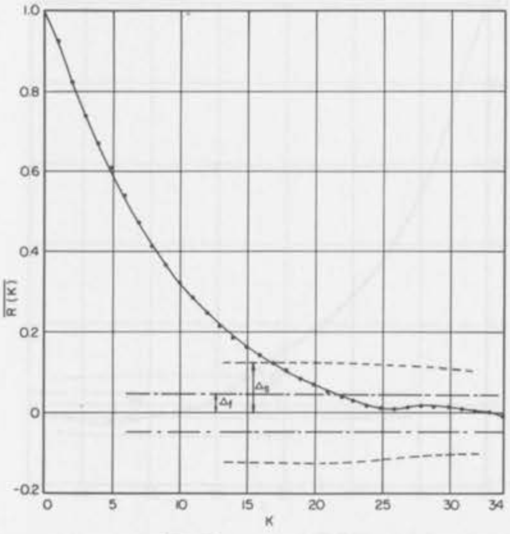
Station	12		16		17		18		19		21		22		25		26		30	
Lag K days	$\overline{R(k)}$	Var(R)	$\overline{R(k)}$	Var(R)	$\overline{R(k)}$	Var(R)	$\overline{R(k)}$	Var(R)	$\overline{R(k)}$	Var(R)	$\overline{R(k)}$	Var(R)	$\overline{R(k)}$	Var(R)	$\overline{R(k)}$	Var(R)	$\overline{R(k)}$	Var(R)	$\overline{R(k)}$	Var(R)
1	.931	.0006	.912	.002	.924	.0014	.889	.004	.940	.0008	.954	.0006	.927	.001	.916	.001	.897	.003	.923	.002
2	.809	.0037	.786	.013	.823	.008	.737	.021	.842	.005	.869	.004	.793	.009	.795	.008	.775	.008	.806	.009
3	.689	.008	.679	.026	.739	.017	.623	.038	.742	.012	.785	.011	.661	.019	.694	.018	.661	.018	.699	.020
4	.584	.011	.602	.033	.670	.025	.551	.043	.652	.020	.710	.019	.550	.025	.613	.027	.568	.027	.607	.030
5	.490	.001	.545	.034	.607	.033	.504	.042	.573	.028	.645	.026	.450	.030	.545	.036	.492	.037	.531	.037
6	.404	.015	.489	.038	.540	.042	.450	.046	.502	.035	.585	.032	.360	.035	.479	.047	.433	.046	.466	.042
7	.330	.020	.427	.046	.474	.049	.383	.056	.439	.040	.534	.035	.286	.039	.413	.058	.377	.058	.407	.046
8	.272	.024	.369	.053	.416	.053	.326	.067	.385	.045	.493	.037	.227	.046	.354	.067	.327	.069	.355	.049
9	.224	.027	.320	.059	.368	.059	.280	.072	.336	.048	.456	.036	.178	.051	.305	.072	.284	.076	.310	.052
10	.180	.029	.282	.064	.325	.061	.239	.072	.290	.054	.422	.037	.135	.051	.264	.070	.248	.080	.271	.054
11	.138	.028	.250	.065	.288	.066	.202	.067	.245	.059	.384	.041	.101	.048	.229	.063	.220	.081	.238	.055
12	.100	.028	.219	.064	.251	.070	.167	.064	.206	.065	.345	.047	.073	.047	.196	.060	.189	.085	.209	.055
13	.059	.031	.191	.063	.215	.072	.132	.064	.171	.069	.302	.056	.054	.046	.163	.059	.161	.090	.182	.057
14	.021	.034	.166	.063	.186	.072	.101	.063	.137	.069	.259	.065	.040	.046	.135	.059	.136	.099	.158	.059
15	-.011	.036	.146	.063	.163	.071	.074	.063	.107	.067	.220	.075	.029	.046	.113	.061	.117	.107	.136	.061
16	-.040	.033	.121	.064	.141	.071	.060	.061	.080	.063	.184	.085	.016	.047	.102	.063	.100	.113	.112	.063
17	-.064	.030	.100	.066	.123	.068	.045	.060	.053	.061	.152	.094	-.002	.046	.092	.066	.086	.115	.089	.064
18	-.088	.029	.087	.065	.106	.065	.033	.060	.030	.059	.125	.101	-.021	.046	.081	.068	.075	.112	.064	.066
19	-.110	.031	.079	.059	.089	.064	.025	.062	.010	.061	.093	.109	-.042	.047	.069	.070	.065	.108	.041	.070
20	-.134	.036	.066	.054	.071	.064	.018	.067	-.009	.061	.061	.113	-.063	.046	.056	.071	.054	.100	.019	.074
21	-.164	.039	.049	.052	.055	.066	.004	.078	-.030	.062	.030	.114	-.083	.043	.045	.073	.045	.092	-.001	.075
22	-.190	.042	.032	.050	.043	.068	-.010	.082	-.051	.061	.009	.114	-.098	.039	.034	.076	.038	.087	-.014	.074
23	-.202	.042	.020	.048	.031	.070	-.025	.079	-.067	.060	-.006	.117	-.108	.036	.027	.080	.031	.084	-.023	.072
24	-.201	.044	.017	.045	.020	.069	-.029	.076	-.077	.060	-.018	.124	-.116	.034	.035	.079	.031	.082	-.023	.071
25	-.196	.048	.019	.043	.015	.067	-.025	.078	-.084	.060	-.030	.130	-.121	.035	.044	.080	.031	.080	-.032	.071
26	-.193	.051	.022	.042	.013	.061	-.031	.073	-.091	.060	-.043	.134	-.125	.037	.050	.081	.031	.077	-.037	.071
27	-.187	.055	.024	.042	.016	.057	-.029	.067	-.100	.058	-.056	.137	-.127	.038	.053	.080	.029	.076	-.041	.070
28	-.181	.059	.024	.044	.020	.053	-.024	.062	-.111	.057	-.068	.139	-.125	.039	.057	.079	.025	.078	-.044	.069
29	-.178	.062	.016	.046	.019	.051	-.024	.058	-.121	.056	-.077	.139	-.119	.038	.062	.075	.024	.081	-.045	.068
30	-.174	.060	.007	.046	.018	.050	-.017	.052	-.129	.055	-.080	.137	-.113	.036	.061	.072	.027	.086	-.041	.068
31	-.171	.057	-.001	.048	.011	.050	-.024	.044	-.134	.052	-.077	.136	-.110	.034	.048	.065	.021	.088	-.032	.070
32	-.162	.053	-.008	.052	.006	.052	-.035	.037	-.141	.052	-.071	.131	-.114	.033	.031	.059	.019	.087	-.028	.070
33	-.155	.051	-.012	.056	.002	.055	-.041	.035	-.143	.053	-.063	.123	-.113	.033	.016	.054	.013	.085	-.022	.072
34	-.152	.048	-.016	.063	-.004	.059	-.040	.034	-.142	.054	-.060	.118	-.109	.034	-.002	.053	.002	.084	-.016	.074



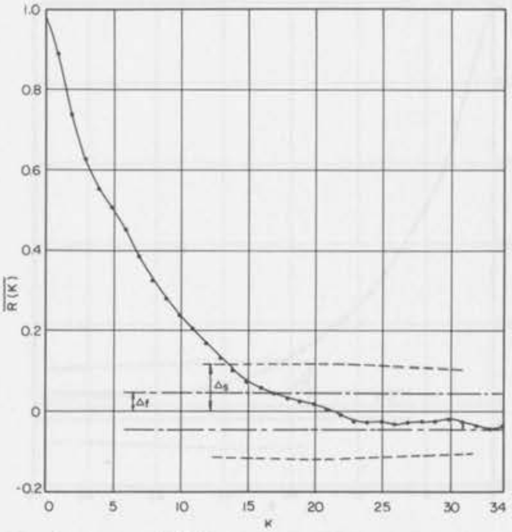
Correlogram: $\overline{R(k)}$ versus k for station 12



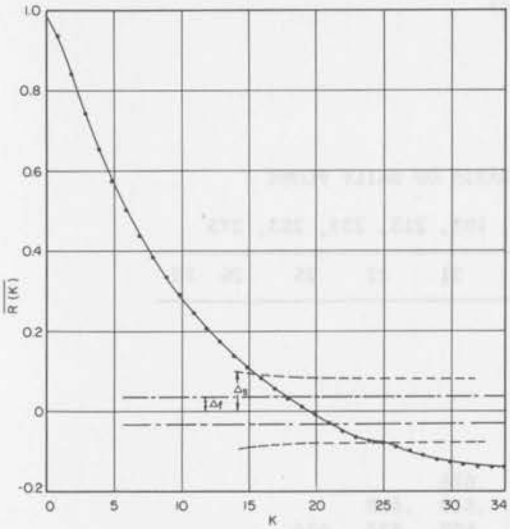
Correlogram: $\overline{R(k)}$ versus k for station 16



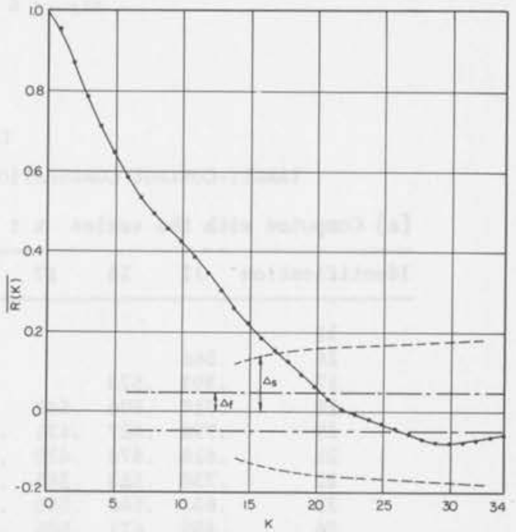
Correlogram: $\overline{R(k)}$ versus k for station 17



Correlogram: $\overline{R(k)}$ versus k for station 18

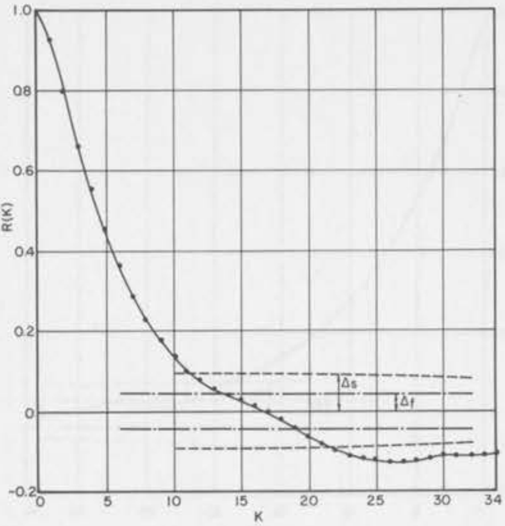


Correlogram: $\overline{R(k)}$ versus k for station 19

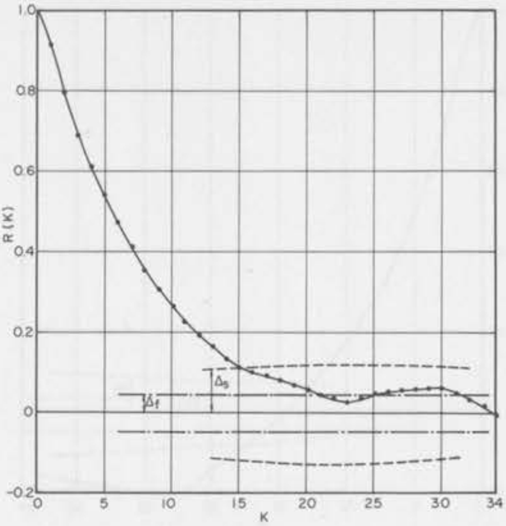


Correlogram: $\overline{R(k)}$ versus k for station 21

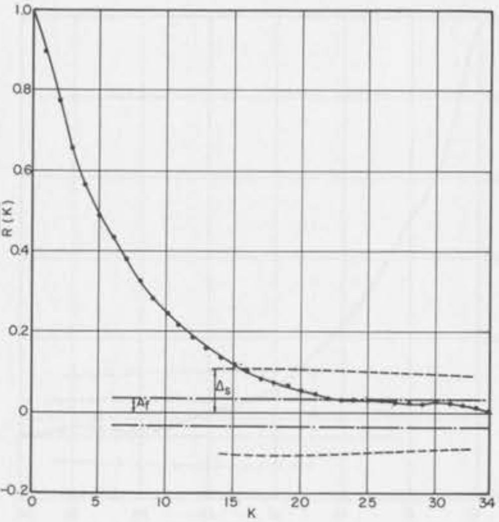
Figure 6



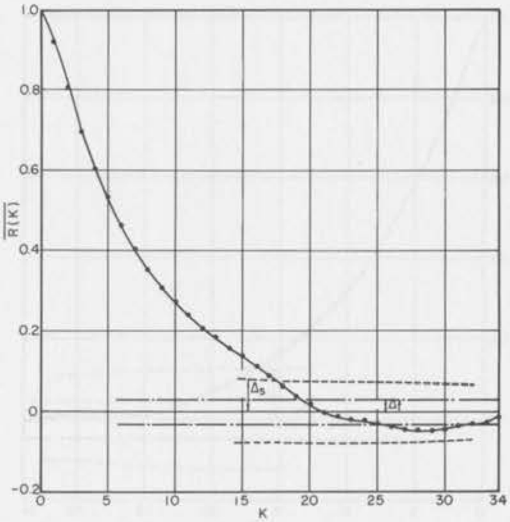
Correlogram: $\overline{R(k)}$ versus k for station 22



Correlogram: $\overline{R(k)}$ versus k for station 25



Correlogram: $\overline{R(k)}$ versus k for station 26



Correlogram: $\overline{R(k)}$ versus k for station 30

Figure 6 (continued)

TABLE 7

TARGET-CONTROL CORRELATION ON THE BASIS OF DAILY FLOWS

[a] Computed with the series t : 153, 173, 193, 213, 233, 253, 273

Identification	**12**	**16**	**17**	**18**	**19**	**21**	**22**	**25**	**26**	**30**
12										
16	**.566**									
17	**.393**	**.523**								
18	**.710**	**.806**	**.549**							
19	**.798**	**.627**	**.431**	**.637**						
21	**.618**	**.674**	**.470**	**.732**	**.644**					
22	**.730**	**.553**	**.385**	**.576**	**.761**	**.676**				
25	**.632**	**.560**	**.550**	**.629**	**.614**	**.510**	**.489**			
26	**.495**	**.621**	**.506**	**.602**	**.502**	**.503**	**.433**	**.616**		
30	**.701**	**.666**	**.552**	**.796**	**.677**	**.722**	**.720**	**.667**	**.541**	

TABLE 7 (continued)

TARGET-CONTROL CORRELATION ON THE BASIS OF DAILY FLOWS

[b] Computed with the series t : 150, 170, 190, 210, 230, 250, 270

Identification	12	16	17	18	19	21	22	25	26	30
12										
16	.615									
17	.463	.557								
18	.696	.808	.471							
19	.740	.625	.503	.598						
21	.563	.623	.408	.604	.557					
22	.712	.620	.463	.625	.737	.590				
25	.641	.656	.641	.658	.683	.436	.592			
26	.552	.641	.582	.646	.498	.495	.511	.618		
30	.668	.659	.599	.727	.604	.681	.697	.680	.547	

Chapter VI

DETECTION OF THE SUSPECTED CHANGE IN RUNOFF

In summary the theoretical analysis of the previous chapters and its application to actual records of daily runoffs at several gage stations have shown that by considering a set of days, whose adjacent elements are lagged by $K = 20$ days, ν independent standardized values of daily flow can be selected within each year, more precisely within each spring season. The lag of 20 days is common to all investigated stations. In other words a random function is selected whose ν ordinates are statistically independent; each ordinate being a random variable with zero mean and unit variance whose distribution is approximately normal.

Therefore, these ν ordinates can be considered as ν independent values of the same normally distributed random variable y. Then in n years of historical records there are $N = \nu n$ independent values of a random variable y whose probability distribution is the standard normal distribution.

During the period of the suspected change the actual daily runoff observations for the corresponding dates provide a new sequence. One suspects that this sequence belongs to a different statistical population than the previous or historical one.

If this is the case and if the new set of data is standardized, according to eq. (4), where the estimates of $P(t)$ and $S(t)$ are the ones obtained based solely on the historical records, the new (historically) standardized daily flow sequence will no longer have zero mean and unit variance. The application of the target-control test will tell whether the change is significant or not. If data are available, grinding the answer from the programmed test subroutine is all that is left to do. On the other hand, if experiments are contemplated for the future and data therefore are not yet available, the required duration of the experiments can be inferred from a randomly generated sequence of daily flows. Of course, the data generation implies a model of what is likely to happen, based on an understanding of the physical phenomena and available experimental evidence.

6.1 Model for the effects of seeding. In the following it is assumed:

(a) Cloud seeding operations increase the values of the streamflows, and, more precisely, they increase the mean daily values $P(t)$.

(b) They do not affect the variance $S^2(t)$ of the daily flows.

(c) The relative increase, h, due to artificial precipitation is independent of time at least throughout the spring season (March to June).

These assumptions are more likely to be correct for cloud seeding operations taking place in winter above watersheds of high elevations--these operations attempt to increase the snowpack and only affect the streamflow during the melting season. The Bureau of Reclamation's pilot project in the Upper Colorado River Basin fits this category.

With the above assumptions, a value of daily flow $Q^*(t)$, affected by cloud seeding experiments, would have the form:

$$Q^*(t) = (1+h)P(t) + S(t)y(t)$$

where h is the relative increase in the mean daily value due to cloud seeding. The historical standardization of $Q^*(t)$ will give $\eta(t)$:

$$\eta(t) = \frac{Q^*(t) - \hat{P}(t)}{\hat{S}(t)} = h\,\frac{\hat{P}(t)}{\hat{S}(t)} + y(t)$$

where $y(t)$ would be the standardized value of $Q^*(t)$ if no increase h, due to cloud seeding, had happened. It follows that $y(t)$ is normally distributed with mean zero and variance unity and we have for a given t:

$E[\eta(t)] = E[h\,\frac{\hat{P}(t)}{\hat{S}(t)}]$, different from zero if h is different from zero.

It is assumed that artificial precipitation has not increased the statistical dependence between daily flows, and that adjacent daily flows, separated by the previously selected lag time k, can be considered as independent. Then, for m years of seeding experiments, $M = m\nu$ independent values of a random variable, η can be selected, whose distribution is assumed to be normal with mean: $E[h\,\frac{\hat{P}(t)}{\hat{S}(t)}]$, where t can take ν values. It should be noted that if $h\,\frac{\hat{P}(t)}{\hat{S}(t)}$ is constant for any of the t for the selected η values, then $\mathrm{var}\,[\eta] = \mathrm{var}\,[y] \simeq 1$. The fluctuation of $h\,\frac{\hat{P}(t)}{\hat{S}(t)}$ with t, being small during the spring season, it can be assumed without much error that $\mathrm{var}\,[\eta] = \mathrm{var}\,[y]$.

6.2 Generation of seeded data. Monte Carlo Method. According to the general model for the seeded period, the variable for the control watersheds is $\xi(t)$ and is normally distributed with mean zero and variance unity. The variable for the target watershed is $\eta^*(t)$ such that:

$$\eta^*(t) = \eta(t) + h\,\frac{\hat{P}(t)}{\hat{S}(t)}.$$

and $\eta(t)$ is correlated to $\xi(t)$ by the regression line obtained for the non-seeded period:

$$\eta(t) = b\xi(t) + \varepsilon(t) \;;$$

where b is the estimate of the slope of the regression line and $\varepsilon(t)$ is the random deviation of $\eta(t)$ about its estimate by the regression line. The joint distribution of (η,ξ) being assumed bivariate normal, $\varepsilon(t)$ is normally distributed around zero with variance $(1-\rho^2)$ $\mathrm{var}[\eta(t)]$ where ρ is the correlation coefficient between ξ and η, then:

$$\eta^*(t) = b\xi(t) + \varepsilon(t) + h\,\frac{\hat{P}(t)}{\hat{S}(t)}$$

To generate data, ρ and b must be calculated for the pair of considered watersheds. Then independent random values are drawn

(a) For $\xi(t)$ from a normal population with mean zero and variance unity.

(b) For $\varepsilon(t)$ from a normal population with mean zero and variance $(1-\rho^2)$.

This was done with the computer CDC 6400 at the University. A subprogram, "Function Ranf" has been written by the University computer center to generate random numbers between 0 and 1, with a uniform density. (The procedure for transformation of this uniform density onto a normal one is described in Appendix 2.)

6.3 Results of the Student-t Test. According to the formulas and derivations given previously, the test was performed for the 10 pairs of stations with correlation coefficient larger than 0.70. For the seeded period the number of years was increased from 1 to 20 until significance at the 95% level (corresponding to a two-tailed test) was reached.

Results are also given for some stations at the 98% and 99% level for a two-tailed test, and at the 95% level for a one-tailed test. The results show (Table 8):

(a) Almost identical results are obtained by using a one-tailed test and a two-tailed test at the 95% level.

(b) Sometimes the same pair of watersheds shows very different results when their status of target and control is permuted. For example: Pair 16-18, with 16 as a target, required one year to show significance but pair 16-18, with 18 as a target, required more than 20 years. This could be because station 18 may not be suitable for a target. According to the way that data for the seeded period were generated, a watershed is suitable as a target if the ratios $\frac{P(t)}{S(t)}$ are large, for the seven selected days, in other words if the $C_v(t) = \frac{S(t)}{P(t)}$ are small. The coefficients of variation $C_v(t)$ were in fact smaller for station 16 than for station 18, but their ratios were much smaller than $\sqrt{20}$, which is the square root of the ratio of the required number of years for significance. Therefore, the differences in the coefficients of variation is not sufficient to explain the difference in the required number of years for significance. A more likely explanation lies in the paucity of the generated random data. In each case only one sequence of data was generated. Therefore, no power value can be attributed to the calculated number of years. It should be also noted from Table 2 that station 18 has probably the least reliable record of all.

(c) The consistency of the results for station 30, paired successively with a different control, is an encouraging result. It was somewhat expected, since the correlation coefficients between station 30 and these control watersheds are of the same order of magnitude. On the other hand, station 12, used as a target successively with a different control, shows great inconsistencies.

TABLE 8

RESULTS OF THE STUDENT t TEST FOR THE DETECTION OF A 10% INCREASE IN THE "DAILY MEANS"

Identification		Number of years in common for the non-seeded period	Number of years for significance and corresponding t						
			with a 2-tailed test						1-tailed test
			95% level		98% level		99% level		95% level
Target	Control		N(yrs)	t	N(yrs)	t	N(yrs)	t	N
12	18	21	5	1.96					
12	19	25	G.T.20						
12	22	23	3	2.74	3	2.74	3	2.74	2
12	30	25	10	1.95					
16	18	21	1	2.58	1	2.58	3	2.75	1
18	12	21	5	2.15					5
18	16	21	G.T.20						
18	21	20	G.T.20						
18	30	21	3	2.68	3	2.68	3	2.68	3
19	12	25	1	3.68	1	3.68	1	3.68	1
19	22	23	2	3.48	2	3.48	2	3.48	2
21	18	20	1	3.44	1	3.44	1	3.44	1
21	30	20	10	1.99					9
22	12	23	2	2.28	4	3.21	4	3.21	2
22	19	23	G.T.20						
22	30	23	8	2.43	8	2.43			
30	12	25	6	2.10	7	2.58	8	2.92	6
30	18	21	4	2.38	4	2.38			3
30	21	20	4	2.37	4	2.37			4
30	22	23	4	2.02					

G.T. means greater than

No attempt was made to transform the data prior to the application of the test, because the Student-t test has been shown [11] to be "robust." In other words, the fact that the joint bivariate distribution of the target and control population may not be normal does not affect the test significantly. To sum up the results:

Twelve stations among 20 required five years or less for detection at the 95% level and seven of them required five years or less for detection at the 99% level.

Only six stations among 20 required 10 years or more for detection at the 95% level.

On the basis of the following formula derived from a Chi-square test:

$$M = 4(1-\rho^2)\,\frac{C_{v,T}^{\,2}}{h^2} \quad \text{(already given in Chapter I),}$$

and using seasonal flows as variables, the number of years M required to detect a $h = 10\%$ increase in the mean seasonal flows at the 95% level and 50% power was computed. Computations were made by using the correlation coefficient ρ between target and control for the six month period (March-August), and the coefficient of variation of the target $C_{v,T}$ for the six month period, then for the four month period (April-July). Results are shown in Table 9.

For 15 stations among 20, the use of daily flows reduced the number of years required for detection in a very significant manner (by an average factor of five over 14 studied cases).

For only three stations out of 20 the use of daily flows was found to be a disadvantage.

TABLE 9

NUMBER OF YEARS REQUIRED FOR THE DETECTION OF A 10% INCREASE IN THE MEANS AT THE 95% LEVEL

Identification		Correlation coefficient with		Target coefficient of variation		Number of years for significance using		
Target	Control	Daily flows	Seasonal flows	4 months period	6 months period	4 months Seasonal flows M4(yr)	6 months Seasonal flows M6(yr)	Daily flows Md(yr)
12	18	.710	.728	.246	.255	11	12	5
12	19	.798	.940	.246	.255	3	3	G.T.20
12	22	.730	.807	.246	.255	8	9	3
12	30	.701	.785	.246	.255	8	10	10
16	18	.806	.969	.515	.504	6	6	1
18	12	.710	.728	.575	.537	62	54	5
18	16	.806	.969	.575	.537	8	7	G.T.20
18	21	.732	.811	.575	.537	45	39	G.T.20
18	30	.796	.877	.575	.537	30	27	3
19	12	.798	.940	.313	.312	4	4	1
19	22	.761	.792	.313	.312	15	14	2
21	18	.732	.811	.572	.510	45	35	1
21	30	.722	.848	.572	.510	37	29	10
22	12	.730	.807	.338	.326	16	15	2
22	19	.761	.792	.338	.326	17	16	G.T.20
22	30	.720	.914	.338	.326	8	7	8
30	12	.701	.785	.428	.413	28	26	6
30	18	.796	.877	.428	.413	17	16	4
30	21	.722	.848	.428	.413	20	19	4
30	22	.720	.914	.428	.413	12	11	4

6 months: March-August
4 months: April-July
G.T. means greater than.

Chapter VII

CONCLUSIONS

1. The standardization of the daily streamflows time-series did not provide stationarity in the wide sense, except for the spring period.

2. The watersheds under study had nearly identical hydrologic features, particularly the same hydrographs; as a result very similar correlograms were found for every station. The study was made possible because all the watersheds had the same stochastic structure, which made it possible to select sequences of independent daily flow values at dates and intervals common to every station.

3. The daily flow time-series show strong autocorrelation. Accordingly, only seven days with independent flow values per year could be selected.

4. The correlation between target and control watersheds, computed on the basis of the independent daily flow sequence, was found to be lower than the one computed on the basis of the corresponding seasonal flow. It was also found to be a good tool to select watersheds having the same hydrologic behavior.

5. The application of a Target-Control Student t-test shows that the use of daily flow as a variable instead of seasonal flow, by increasing the size of the sample, tends to reduce significantly the number of years required to detect a 10% increase in the mean flow at the 95% confidence level.

The most desirable properties that characterize the methods of statistical evaluation are applicability, generality, and power.

Applicability and generality remain open questions since this study considered only the case of winter seeding operations above high elevation watersheds. It is felt the method presented in this paper can be extended to different types of basins as long as they are hydrologically homogeneous, and can be used, not only for evaluation of weather modification, but also for the detection of changes in watershed responses, as long as the effects of such changes are changes in the mean flows, leaving the variance unchanged. For instance, effects of forest fires, land slides, and even urbanization could be investigated in a similar manner.

The sharp power of detection seems to be the best quality of the method. No conclusion can be reached for a particular pair of target-control watersheds as to the value of daily versus seasonal flow for minimal time evaluation because only one sequence of data was generated per pair. On the other hand the ensemble of the results shows rather clearly that the potential value of daily runoff as a detector of change in watershed response is high. The factor of reduction from its use averages three for the 20 cases studied. It is highly significant, and fully justifies additional more complete and more refined studies.

LIST OF SYMBOLS

Symbol	Description
$Q(t)$	Random function whose values are the daily flow values
$P(t)$	"Mean for a given day," i.e., mean daily value of $Q(t)$
$S(t)$	Standard deviation of $Q(t)$ for a given t
$q_i(t)$	Standardized daily flow values
t	Index referring to a day within a given year
i	Index referring to a year
n	Number of years of historical record for the non-seeded period
m	Number of years of record for the seeded period
N	Number of data or sample size for the non-seeded period
M	Number of data or sample size for the seeded period
y	Series of independent standardized daily flows for the non-seeded period of the target
η	Series of independent standardized daily flows for the seeded period of the target
x	Series of independent standardized daily flows for the non-seeded period of the control
ξ	Series of independent standardized daily flows for the seeded period of the control
$Q^*(t)$	Daily flow values affected by seeding operations
$r_k(t)$	Correlation coefficient between day t and day $t-k$
$R_i(k)$	Serial correlation coefficient for lag k and for year i
$\overline{R}(k)$	Average of $R_i(k)$ over n realizations
ρ	Target-control correlation coefficient
ν	Number of independent daily flow values for the spring season
b	Slope of the regression between target and control
$\hat{\ }$	The "hat" over a symbol means: we are considering the sample estimate of a given parameter
$*$	The "star" next to a symbol means: suspected to come from a different population than in the past.

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APPENDIX 1

Fitting Markov I Model

The asymptotic behavior of the correlograms suggests the daily flow series could be fitted by a first order linear autoregressive scheme (or Markov first order linear model).

In this model, the correlogram of y(t) can be represented by

$$R(k) = a^k$$

and the autoregressive scheme is given by:

$$y(t) = ay(t-1) + \varepsilon(t)$$

where $\varepsilon(t)$ is independent of y(t-1), y(t-2)... and of the other ε's. Then a could be estimated either by

(1) taking a = R_1 (empirical value of the first autocorrelation coefficient)

(2) fitting a function $R(k) = a^k$ to the empirical correlogram and estimating the value of a by the method of least square, which could be done by linearizing the exponential function before minimizing the sum of the squared differences. Criterion or a test for goodness of fit then can be used to determine how well the Markov I model will apply [19,20].

If such a model would fit well enough, it can be seen that using the series $\varepsilon(t)$ for the purpose of weather modification detection will yield a very large sample, since the ε's are independent. How would the series $\varepsilon(t)$ be affected by artificial precipitation? For the non-seeded period:

$$\varepsilon(t) = y(t) - ay(t-1)$$

and $\varepsilon(t)$ has a mean equal to zero and a variance:

$$\text{var}[\varepsilon(t)] = (1-a)^2 \text{ var}[y(t)] = 1-a^2 \ .$$

For the seeded period:

$$\varepsilon^*(t) = y(t) - ay(t-1) + h\left(\frac{P(t)}{S(t)} - a\frac{P(t-1)}{S(t-1)}\right) .$$

If we compare the series $\varepsilon(t)$ with the series y(t) involving seven data points per year, we find:

(a) The expectation of $\varepsilon^*(t)$ is roughly (1-a) times the expectation of $\eta(t)$,

(b) The standard deviation of $\varepsilon^*(t)$ is $\sqrt{1-a^2}$ times the deviation of y(t),

(c) For $\varepsilon(t)$ the number of data points per year is g = 14.7 times the one for the series y(t).

We shall assume that the correlation between target and control on the basis of the $\varepsilon(t)$ is the same as the one on the basis of the y(t). In fact it is likely to be much smaller. Denoting the number of necessary years for detection by the series $\varepsilon(t)$ and y(t) respectively by M_ε and M_y and ($\sim$) being the symbol of proportionality, we have

$$\frac{M_\varepsilon}{M_y} \sim \frac{t_{95,\varepsilon}}{t_{95,y}} \cdot \frac{\sqrt{1-a^2}}{(1-a)\sqrt{g}}$$

$$\frac{M_\varepsilon}{M_y} \sim \frac{t_{95,}}{t_{95,y}} \cdot \sqrt{\frac{1+a}{(1-a)g}} \ .$$

The number of degrees of freedom for $t_{95,\varepsilon}$ will be roughly g times the one for the $t_{95,y}$. But since the latter is already a large number, the ratio

$$\frac{t_{95,\varepsilon}}{t_{95,y}}$$

will be very close to one.

With two stations with n years of historical records and five years of seeded period we would have:

$$\frac{t_{95,\varepsilon}}{t_{95,y}} \simeq .99$$

Taking a = 0.9, we would find:

$$\frac{M_\varepsilon}{M_y} \simeq .99 \times 1.14 = 1.13 \ .$$

Taking a = 0.95, we would find:

$$\frac{M_\varepsilon}{M_y} \simeq .99 \times 1.64 = 1.62 \ .$$

Fitting the Markov I model would give values of (a) between 0.9 and 0.95, but in any case it would hardly improve the detection possibilities, whereas it would complicate and greatly expand the computations.

It is interesting to note that in the case where the Markov I model describes well our variable, ν, the number of independent days during a G = 103 days period, is given by [21]:

$$\nu = \frac{G}{1 + \frac{2a}{1-a}\left(1 - \frac{1}{G}\frac{1-a^G}{1-a}\right)} \ .$$

With a = 0.9 and G = 103 we find: ν = 6 days, which is the number of independent days we selected for the 103 days period. (The seventh day is outside this interval for which the conditions of stationarity are met.)

APPENDIX 2

The purpose of this Appendix is to describe a method [22] to generate random numbers from a normal population with high accuracy and favorable speed for the computer.

Let U_1 and U_2 be the independent random variables from the same rectangular density $f(U_1,U_2) = 1$, on the interval [0,1] and consider the random variables defined by:

$$X_1 = (-2 \text{ Log}_e\, U_1)^{\frac{1}{2}} \text{ Cos } 2\pi U_2 = g_1(U_1,U_2)$$

$$X_2 = (-2 \text{ Log}_e\, U_1)^{\frac{1}{2}} \text{ Sin } 2\pi U_2 = g_2(U_1,U_2) \quad .$$

We then have:

$$U_1 = e^{\frac{-(x_1^2 + x_2^2)}{2}} = h_1(X_1,X_2)$$

$$U_2 = -\frac{1}{2\pi} \arctan \frac{X_2}{X_1} = h_2(X_1,X_2) \quad .$$

And then we have:

$$P(a \leq U_1 < b,\ c \leq U_2 < d) = \int_a^b \int_c^d f(U_1,U_2)\, du_1\, du_2$$

$$= \int\!\!\int_{(S)} f[h_1(x_1,x_2),\ h_2(x_1,x_2)]\,|J|\, dx_1\, dx_2$$

where (S) is the domain of the x_1, x_2 plane into which the rectangle $(a \leq U_1 < b,\ c \leq U_2 < d)$ is mapped by the transformation, and

$$J = \begin{vmatrix} \partial h_1/\partial x_1 & \partial h_1/\partial x_2 \\ \partial h_2/\partial x_1 & \partial h_2/\partial x_2 \end{vmatrix} \quad .$$

The density function of the joint distribution for (x_1,x_2) is $\psi(x_1,x_2)$; $\psi(x_1,x_2) = f[h_1(x_1,x_2), h_2(x_1,x_2)]\,|J| = |J|$, since $f[\,] = 1$; and we find

$$\psi(x_1,x_2) = |J| = \frac{1}{2\pi}\, e^{\frac{-(x_1^2+x_2^2)}{2}} = \frac{1}{\sqrt{2\pi}}\, e^{\frac{-x_1^2}{2}}\, \frac{1}{\sqrt{2\pi}}\, e^{\frac{-x_2^2}{2}}$$

$$= \psi(x_1)\psi(x_2) \ ;$$

x_1 and x_2 are a pair of independent random variables from the same normal population with mean zero and unit variance.

In this way we can draw a set of values of $\xi(t)$ and another set of values that once multiplied by $\sqrt{1-\rho^2}$ will give a set of values for $\varepsilon(t)$.

A fortran program was written for this purpose for different pairs of station and for h = 10%.

Key Words: Statistical discrimination, hydrologic change, daily runoff, precipitation management, evaluation

Abstract: The purpose of this study was the development of a technique for rapid detection of the occurrence of a suspected hydrologic change in high mountain watersheds. A method has been developed that uses a sequence of independent daily flows. This procedure is superior to previous ones based on seasonal or yearly flows. The results of this investigation show the use of daily, instead of seasonal flow, data in a Student t-test reduces the number of necessary years of data for detection by an average of five in 14 out of the 20 cases studied, or by an average of three for the 20 cases. All of the cases come from the Upper Colorado River Basin. The study is particularly relevant to the planned cloud seeding operations of the Bureau of Reclamation in high elevation areas of the Colorado Rocky Mountains. The statistical procedure of detection relies on the Target Control concept and the application of a conditional Student t-test, a test of the difference between the adjusted means obtained by the regression lines between Target and Control for the seeded and non-seeded periods.

References: Andre J. Dumas and Hubert J. Morel-Seytoux, Colorado State University Hydrology Paper No. 34 (August 1969) "Statistical Discrimination of Change in Daily Runoff."

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Appendix 3

SUITABILITY OF THE UPPER COLORADO RIVER BASIN FOR PRECIPITATION MANAGEMENT

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RELATION OF HYDROLOGY PAPER NO. 36 TO RESEARCH PROGRAM: "HYDROLOGY OF WEATHER MODIFICATION"

The present study is part of a more comprehensive project which has as one of its objectives the development of methods of evaluation of atmospheric water resources programs. Correlatively the application of the methods to a variety of basins forms a basis for selection of suitable watersheds, basins or regions.

Several approaches are possible and are pursued. One approach was the subject of a previous hydrology paper, No. 34 (see inside back cover for complete reference). Another approach will be discussed in a forthcoming paper entitled, "Regional Discrimination of Change in Runoff."

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ABSTRACT

The purpose of this study was the determination of suitable watersheds or combinations of watersheds for precipitation management programs in the Upper Colorado River Basin in general and for two special zones: the San Juan Mountains and the Upper Basin of the Colorado River.

The study shows that the introduction of optimal weight factors in the linear combination of runoff from several basins will reduce significantly the number of years necessary for evaluation of the operations. Assuming a uniform 10% increase in winter precipitation throughout the Upper Colorado River Basin, the calculations show that three years of operations would be needed in the Upper Basin of the Colorado versus six years in the San Juan mountains.

SUITABILITY OF THE UPPER COLORADO RIVER BASIN FOR PRECIPITATION MANAGEMENT

by

Hiroshi Nakamichi* and Hubert J. Morel-Seytoux**

Chapter I

INTRODUCTION

1. Water needs of the basin. The Colorado River system is the largest in the United States that flows mainly through lands having a chronic water deficiency for cultivation of crops [1]. Since the 1940's, the basin's population has increased rapidly with an accompanying growth in demand upon the region's water resources for irrigation, industrial, and domestic uses [2]. Over the decade from 1951 through 1960, the population of the five states comprising the Upper Colorado River Basin has increased by 40 percent, while over the same period the population of the nation as a whole has increased only by 20 percent [3].

2. Precipitation management program. In an effort to reduce the severity of these demands, an atmospheric water resource project is currently pursued by the United States Department of the Interior, Bureau of Reclamation, Office of Atmospheric Water Resources. The goal of this project is to induce more precipitation from the atmosphere by winter cloud seeding operations over certain high altitude watersheds in the Upper Colorado River Basin. In the past, there was some controversy as to whether man could economically increase precipitation in worthwhile amounts. There now exists evidence that this is possible at least in high mountain areas [4]. As of February 1969, plans of the Bureau of Reclamation called for a concentrated experimental effort in two pilot areas of the Upper Colorado River Basin, to start in the fall of 1969 [5]. This study was undertaken in connection with the Bureau's overall program in general and in connection with this pilot program in particular.***

3. Criteria of suitability. In the experimental or large-scale operational stage of the project, a site should be selected. At this point, one needs certain criteria in order to select suitable basins. These criteria should be considered both from a water resource and an evaluation standpoint [6]. The first standpoint requires a criterion of suitability for optimal water yield, and the second, a criterion of suitability for minimum time evaluation.

Ideally the criteria should be objective and simple. That is, they should be derived easily from available data rather than from theory. Though various aspects of research on cloud modification have been conducted sucessfully, it is still difficult to determine its quantitative effect. Indeed, one of the purposes of the pilot project is to determine the exact magnitude of the increase in precipitation on a large areal scale. Following this experiment, it may be possible to isolate the major factors that determine the magnitude of the increase in precipitation. Once precipitation is induced, the increase in runoff, (ΔQ), caused by the increase of precipitation, (ΔP), is estimated by a statistical relationship between precipitation and runoff, $(Q = f(P))$, often used when forecasting runoff:

$$\Delta Q = (Q+\Delta Q) - Q = f(P+\Delta P) - f(P) \quad (1)$$

Marginal criteria are defined in order to determine the relative suitability of many potential basins for minimum time evaluation, even if the type of statistical test and the design of the experiment are not known [6]. One such criterion is derived from the "two-sample u-test."

The two-sample u-test is a test of the hypothesis that assumes that the mean of a statistical population (the values of annual runoff for a given basin over many years) has not changed significantly even though there were reasons to suspect it had. As the name implies, the application of the test requires the availability of two samples of data, one sample collected prior to the suspected change and one collected afterward. If the suspected change is real but small, the records of many years may be necessary to determine its significance. If the change is large and the spread of the distribution is narrow, only a few years may be required.

No statistical test is free of assumptions. The two-sample u-test assumes that only the mean of the population may have changed whereas the shape and the spread of the distribution have not. Assuming a normal distribution, the explicit expression [6] for the number of years, N, necessary to guarantee the statistical significance of the observed or expected increase at the 95 percent confidence level is given by:

$$N = \frac{(1.96)^2 \times \sigma_Q^2}{(\Delta Q)^2} = \frac{3.84\, \sigma_Q^2}{(\Delta Q)^2} \quad (2)$$

---

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***Since the initiation of this study the plans of the Bureau were modified. Currently (45) only one area is considered: the San Juan Mountains region.

where σ_Q^2 is the standard deviation of runoff, and

ΔQ is the increase in runoff.

One of the purposes of this study is to determine the relative suitability of individual basins within the Upper Colorado River Basin by calculating the expected increase in runoff for each, i.e., ΔQ, from equation (1) and the number of years needed for evaluation, i.e., N, from equation (2).

On the other hand, the pilot program involves many sub-basins within major ones. In this case, it is advisable to choose a favorable combination of sub-basins for evaluation. For this purpose, a new variable, Q^*, is constructed by a linear combination of n runoff variables, Q_i $(i=1, 2, \ldots, n)$, i.e.,

$$Q^* = \alpha_1 Q_1 + \alpha_2 Q_2 + \ldots + \alpha_n Q_n = \sum_{i=1}^{n} \alpha_i Q_i \tag{3}$$

where Q_i is the runoff from an individual sub-basin. Much freedom is gained from a combination of runoff variables from various basins such as (3) compared to the use of a single basin runoff. The freedom gained is twofold. First, there is freedom gained in the process of selection of n basins among many. For example, where there are 15 ways of selecting one basin out of 15, there are 3003 ways of selecting five basins out of 15. Second, there is freedom gained in the process of selection of the parameters α_i once n sub-basins have been chosen.

However, for hydrologic reasons, two restrictions were imposed on the choice of the parameters α:

(a) The mean of Q^*, $\overline{Q}^*$, must be equal to the sum of the means of the Q_i, $\overline{Q}_i$, symbolically:

$$\overline{Q}^* = \sum_{i=1}^{n} \alpha_i \overline{Q}_i = \sum_{i=1}^{n} \overline{Q}_i \tag{4}$$

and

(b) The expected increase of Q^*, $\overline{\Delta Q}^*$, must be equal to the sum of the expected increases in Q_i, $\overline{\Delta Q}_i$, i.e., symbolically:

$$\overline{\Delta Q}^* = \sum_{i=1}^{n} \alpha_i \overline{\Delta Q}_i = \sum_{i=1}^{n} \overline{\Delta Q}_i \ . \tag{5}$$

The hydrologic interpretation of equation (4) is that the expectation of the random variable Q^* is the mean of the total runoff for the group of n basins. The interpretation of equation (5) is that the expected increase of the mean of Q^* is that of the total runoff for the group of n basins.

As for a single basin the number of years, N^*, needed for evaluation of grouped basins is given by:

$$N^* = \frac{3.84\ \sigma_{Q^*}^2}{(\Delta Q^*)^2} \ . \tag{6}$$

Another purpose of this study is to develop systematic methods to obtain the most favorable combinations of sub-basins in the pilot areas by determining the α_i's such that the number of years, N^*, in equation (6), is kept to a minimum.

4. General plan of paper. In Chapter II, the hydrologic characteristics of the Upper Colorado River Basin are reviewed. In the same chapter, the potential for weather modification in this region is also discussed. Chapter III treats the question of definition of a criterion of suitability and its calculations. Chapters IV and V discuss the data used in the study, the techniques of data processing, and most importantly, the results. Chapter VI concludes the study.

5. Select basic terms used in this study.

(a) Water Year

"Water year" begins October 1 and ends September 30 of the calendar year. The term, "annual," refers to water year. In the text the words "year" and "water year" are used synonymously.

(b) Precipitation

"Precipitation" refers to rainfall and the water content of snow. Winter precipitation includes precipitation from September 1 through April 30 and spring precipitation from May 1 through July 31. Winter precipitation generally falls in the form of snow in the high mountain watersheds. Precipitation is measured in inches.

(c) Runoff

"Runoff" refers to the river flow measured at a gaging station. In this study, unit yield is used, i.e., the depth, in inches, of the cumulative volume of flow during a given period, when volume is spread uniformly over the whole watershed. Spring runoff includes runoff from April 1 through July 31.

(d) Upper Colorado River Basin

By this expression the drainage basin of the Colorado River above Lee's Ferry is meant (see Figure 1).

(e) Upper Basin of the Colorado River

A much smaller drainage basin is meant by this expression. The Upper Basin of the Colorado River is defined in this study as the drainage basin of the main stem of the Colorado, close to its source, and of a few tributaries. The limits of this basin are shown on Figure 6(b).

Chapter II

THE HYDROLOGIC AND HISTORIC SETTING

The hydrologic characteristics of the Upper Colorado River Basin are reviewed. They explain in part the interest in and the potential for weather modification in this area. Certain aspects of the precipitation management program in the Upper Colorado River Basin are discussed briefly.

1. The Upper Colorado River Basin. The Upper Colorado River Basin (Fig. 1) covers parts of the states of Colorado, Wyoming, Utah, New Mexico, and Arizona. It comprises 109,500 square miles above Lees Ferry, Arizona, its boundaries extending along the continental divide in the east and the north and along the divide of the mountain range through Utah in the west. The Colorado River, which is the third longest river in the United States, has a length of 1,450 miles. It has its source in the high, snow-capped mountains in northwestern Colorado. It is also fed by major tributaries originating in other parts

Fig. 1. The Upper Colorado River Basin (after Upper Colorado River Commission [7])

of Colorado; by the Green River originating in Wyoming and flowing into the Colorado River in southern Utah; by the San Juan River originating in southern Colorado, flowing through northern New Mexico and joining the Colorado River in southern Utah. In the northern portion of the basin, there are hundreds of peaks of more than 13,000 feet in elevation. A highly smoothed topography of the basin is shown in Fig. 2.

In high mountain regions, much of the annual runoff occurs as a result of melting snow. Hence, runoff is often characterized by a peak flood season in late spring followed by low water flow in summer, fall, and winter. This holds true for the Colorado River and its tributaries [2].

The annual virgin runoff at Lees Ferry, Arizona, is noted for its large fluctuation, as shown in Fig. 3. Virgin runoff is that runoff which takes place without the interference of man. Virgin runoff is reconstructed from the actual flow, from data on transmountain diversions, on regulation by dams, and from estimates of irrigation diversions and uses. The fluctuation of annual virgin runoff ranges from a low of 1.08 inches to a high of 4.10, as measured in the last 51 years [9].

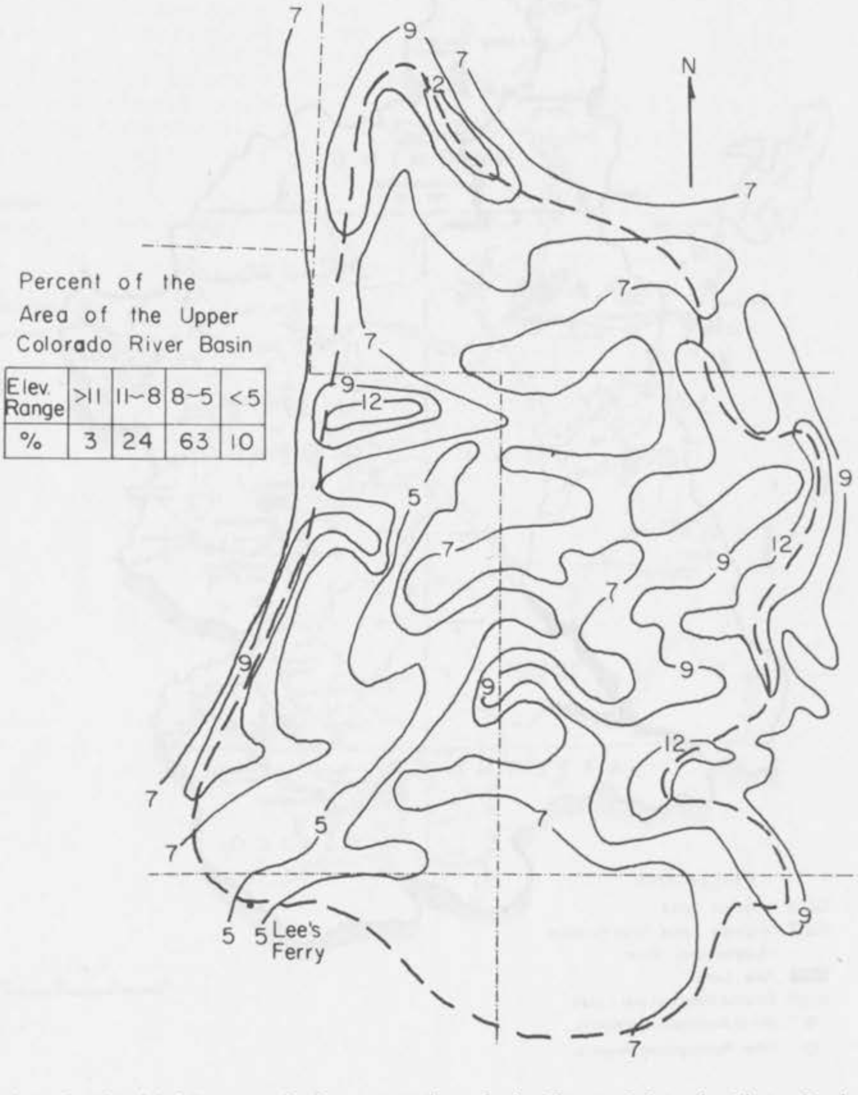
2. Precipitation management in the Upper Colorado River Basin. The precipitation management project, currently planned by the United States Bureau of Reclamation, Office of Atmospheric Water Resources, concerns winter cloud seeding operations above certain high elevation watersheds of the Upper Colorado River Basin. The precipitation due to cloud seeding which falls as snow in winter, is expected to increase the runoff in spring.

The following characteristics of the Upper Colorado River Basin are favorable for weather modification:

(a) High mountain ranges in this region are favorable for orographic precipitation and in addition, the northwest wind brings large supplies of moisture in winter [10].

(b) Water from snowmelt in early spring through early summer can be stored and made available when needed for various kinds of use.

Figures 4 and 5 illustrate the typical variation of precipitation and runoff in this region. The distribution of monthly precipitation is, on the average,



Percent of the Area of the Upper Colorado River Basin

Elev. Range	>11	11~8	8~5	<5
%	3	24	63	10

Fig. 2 The highly smoothed topography of the Upper Colorado River Basin (in units of 1000's of feet). (After Rasmussen, J.L. [8])

uniform. However, the major part of the runoff occurs during the spring and early summer months, which is due primarily to snowmelt.

The design of a moderate scale pilot program of operational seeding is in progress, serving as a bridge between experimental programs and the large-scale operation of the Colorado River Basin [5,11]. The following two areas were selected by the Bureau of Reclamation* for a pilot program.

(1) The San Juan Mountains including drainage areas from Lake Fork, Colorado, to the New Mexico border, and

(2) The Upper Basin of the Colorado River including drainage from Williams Fork, Colorado, to Troublesome Creek, Colorado.

These regions are shown in Fig. 6. The suitability of grouped basins from these regions for weather modification is discussed in Chapter V, Section 5.

The next chapter discusses the question of definition and calculation of suitability criteria. Based on these criteria, the overall suitability of the Upper Colorado River Basin is assessed in general and for the pilot areas in particular in Chapter V, Section 5.

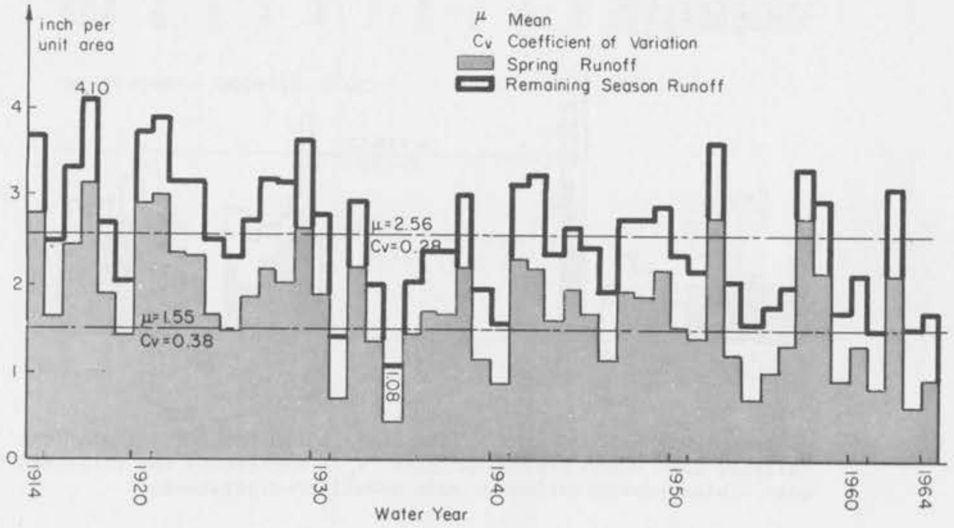


Fig. 3 Annual and spring runoff at Lees Ferry, Arizona

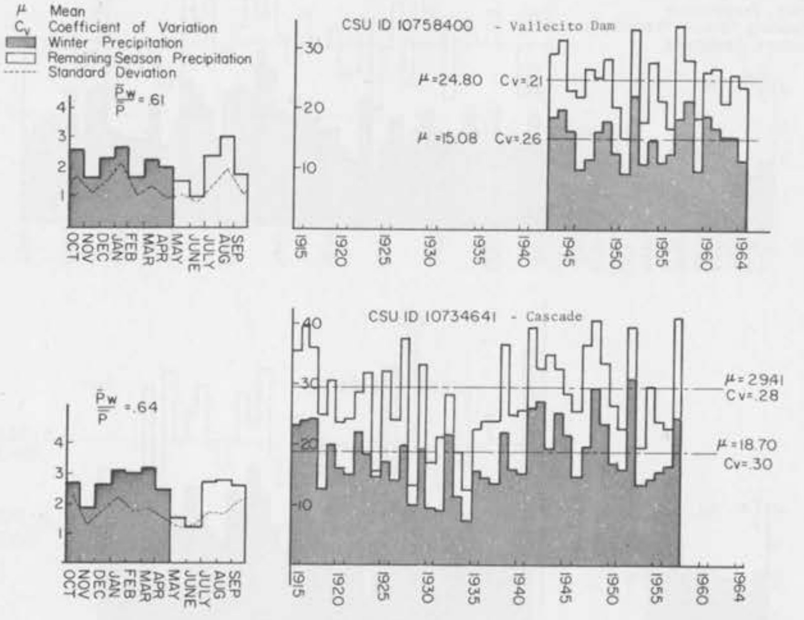


Fig. 4(a) Annual, winter, and monthly precipitation (in inches) for stations Vallecito Dam and Cascade. P_w/P represents the ratio of mean winter precipitation to mean annual precipitation.

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* Since the initiation of this study the plans of the Bureau were modified. Currently (45) only one area is considered: the San Juan Mountains region.

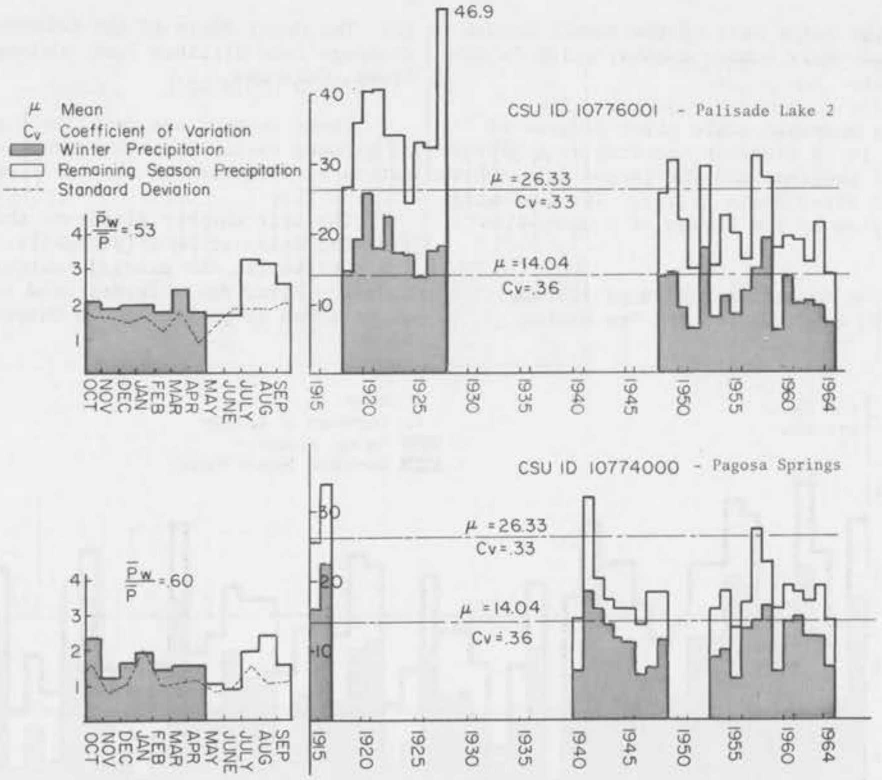

Fig. 4(b) Annual, winter, and monthly precipitation (in inches) for stations Palisade Lake 2 and Pagosa Springs. P_w/P represents the ratio of mean winter precipitation to mean annual precipitation.

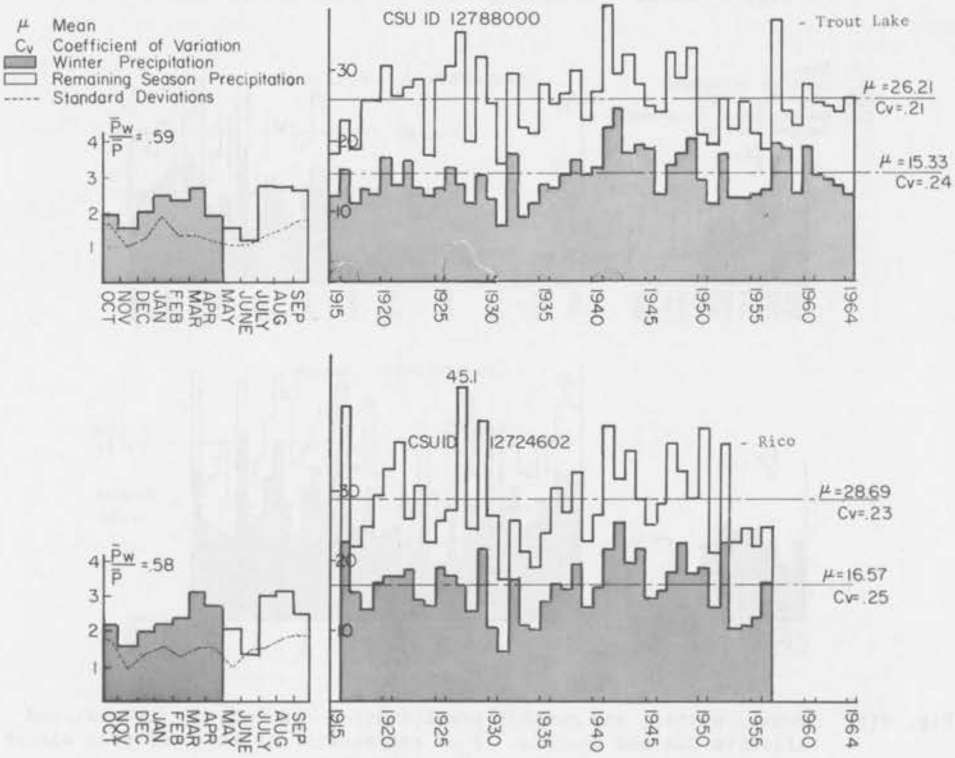

Fig. 4(c) Annual, winter, and monthly precipitation (in inches) for stations Trout Lake and Rico. P_w/P represents the ratio of mean winter precipitation to mean annual precipitation.

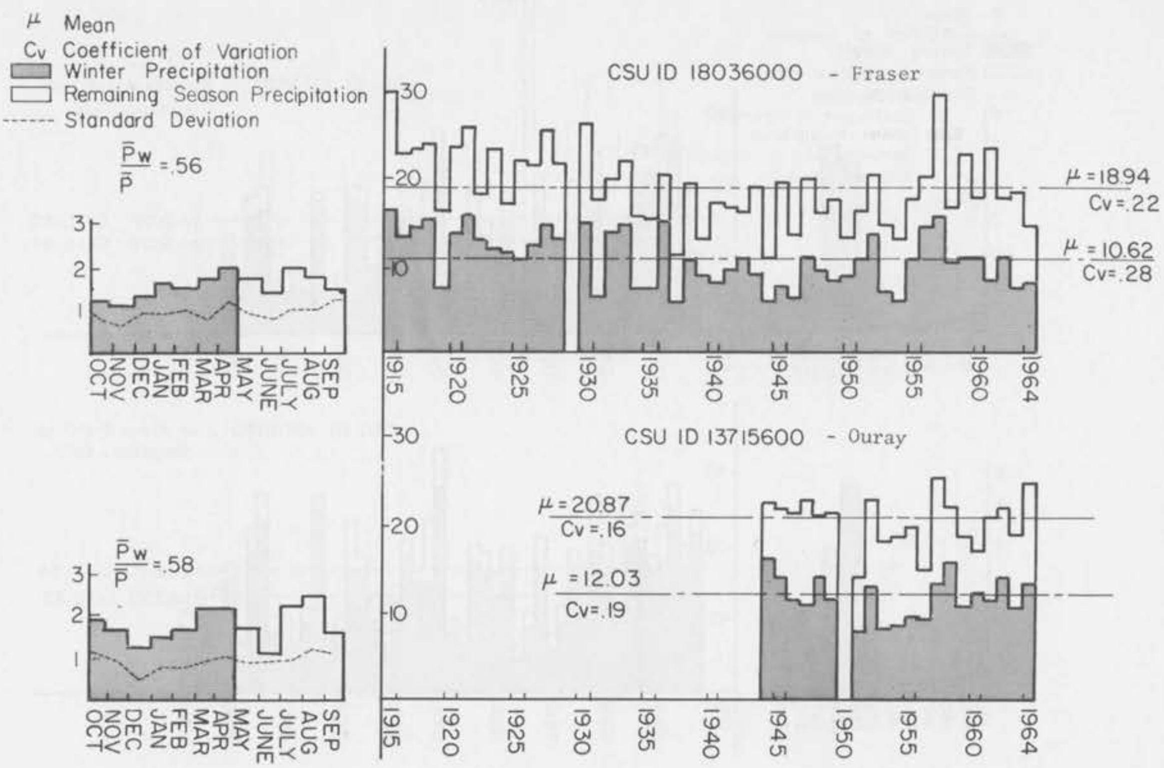

Fig. 4(d) Annual, winter, and monthly precipitation (in inches) for stations Fraser and Ouray. P_w/P represents the ratio of mean winter precipitation to mean annual precipitation.

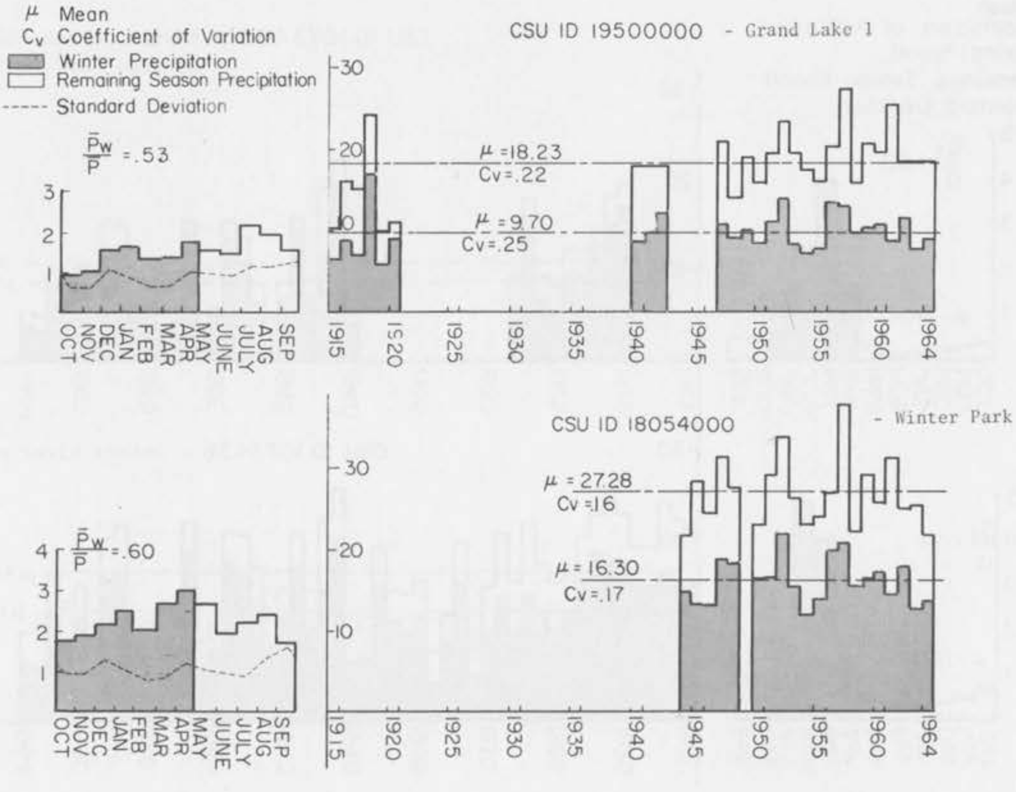

Fig. 4(e) Annual, winter, and monthly precipitation (in inches) for stations Grand Lake 1 and Winter Park. P_w/P represents the ratio of mean winter precipitation to mean annual precipitation.

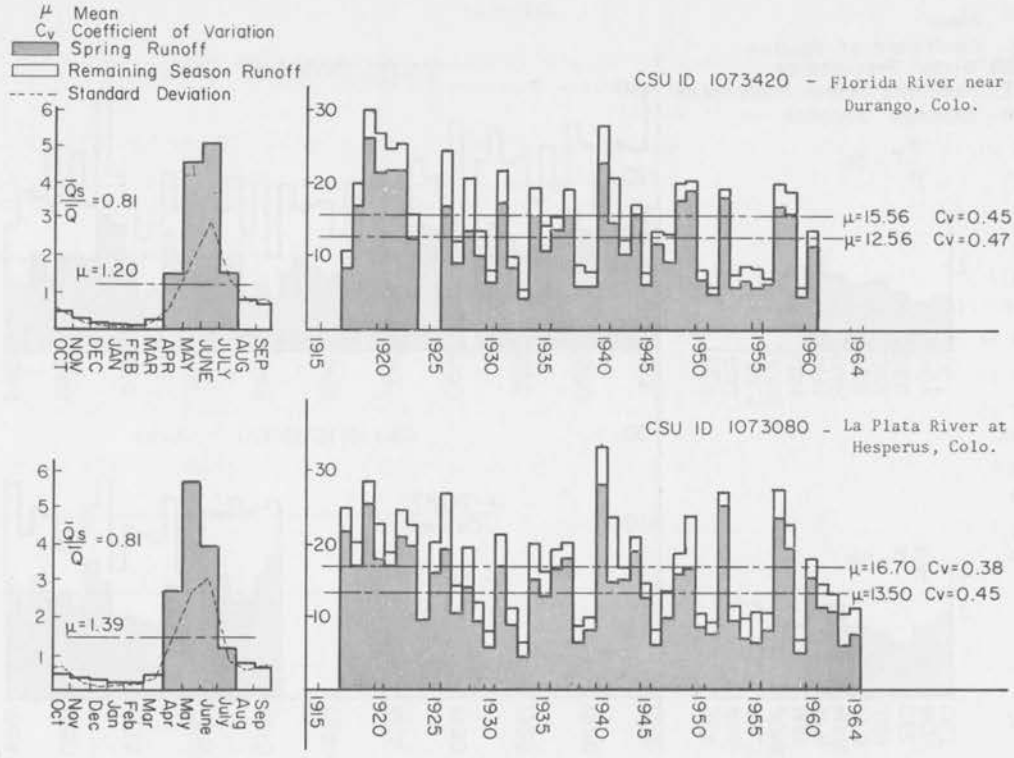

Fig. 5(a) Annual, spring, and monthly runoff (in inches) for stations Florida River near Durango, Colo. and La Plata River at Hesperus, Colo. $\overline{Q}_s/\overline{Q}$ represents the ratio of mean spring runoff to mean annual runoff.

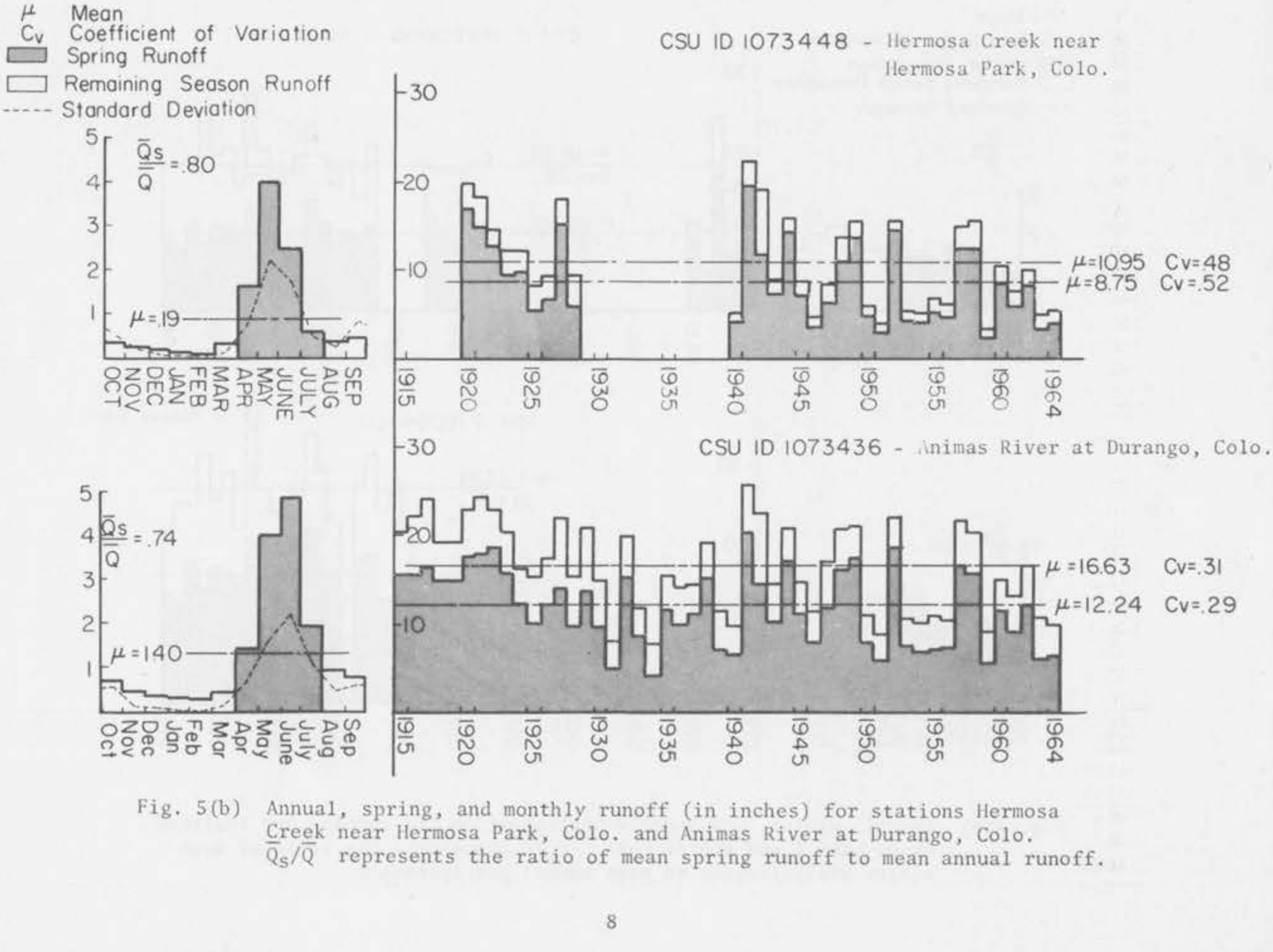

Fig. 5(b) Annual, spring, and monthly runoff (in inches) for stations Hermosa Creek near Hermosa Park, Colo. and Animas River at Durango, Colo. $\overline{Q}_s/\overline{Q}$ represents the ratio of mean spring runoff to mean annual runoff.

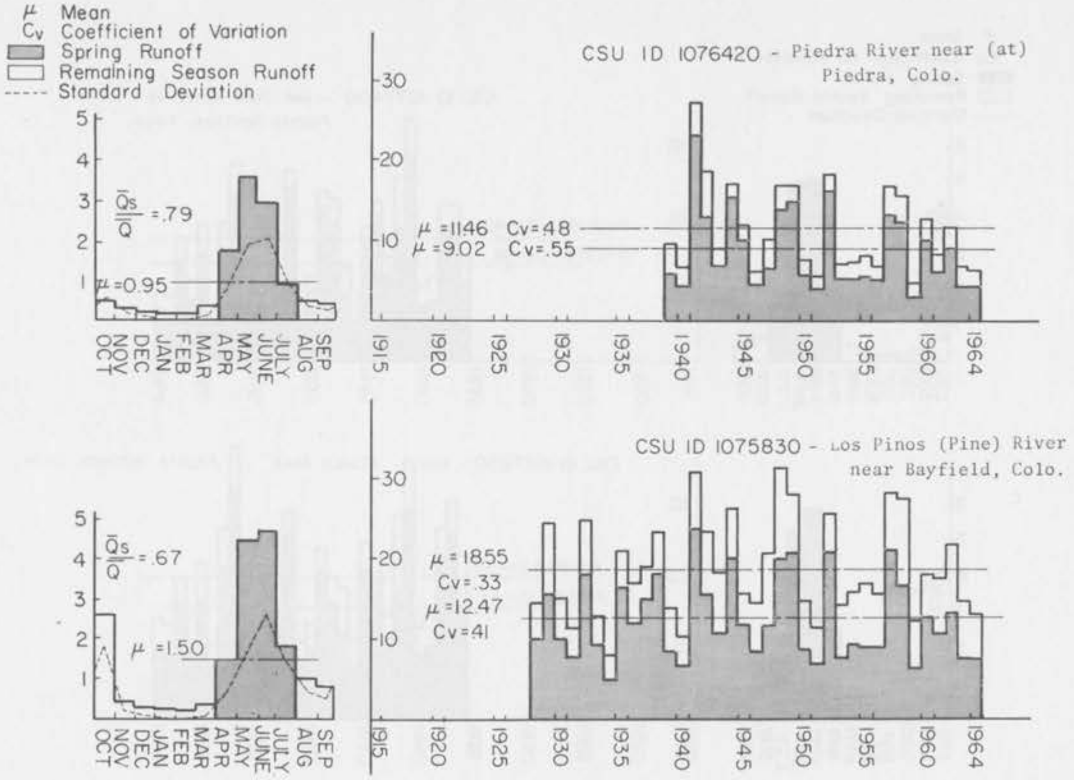

Fig. 5(c) Annual, spring, and monthly runoff (in inches) for stations Piedra River near (at) Piedra, Colo. and Los Pinos (Pine) River near Bayfield, Colo. $\overline{Q}_S/\overline{Q}$ represents the ratio of mean spring runoff to mean annual runoff.

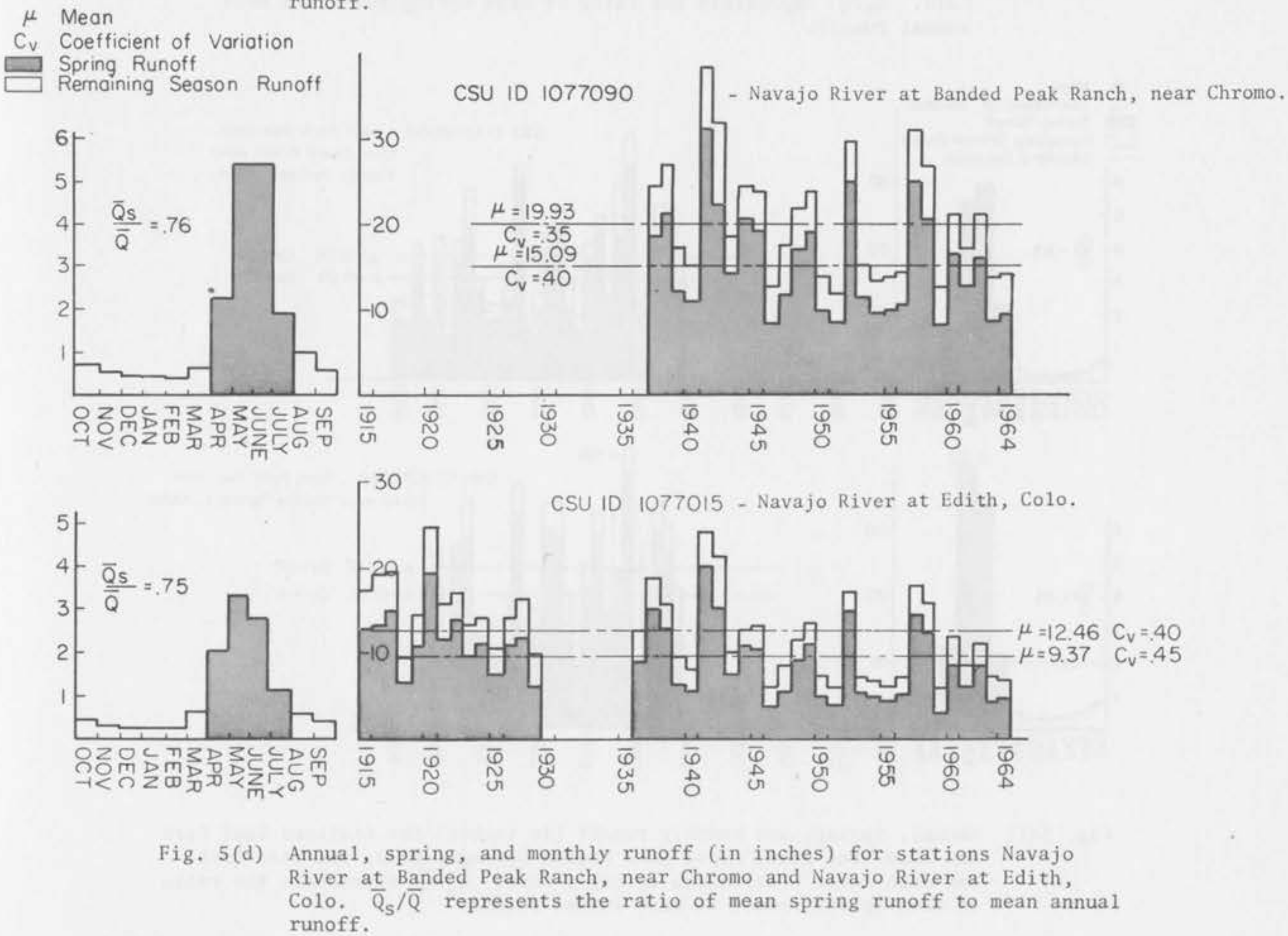

Fig. 5(d) Annual, spring, and monthly runoff (in inches) for stations Navajo River at Banded Peak Ranch, near Chromo and Navajo River at Edith, Colo. $\overline{Q}_S/\overline{Q}$ represents the ratio of mean spring runoff to mean annual runoff.

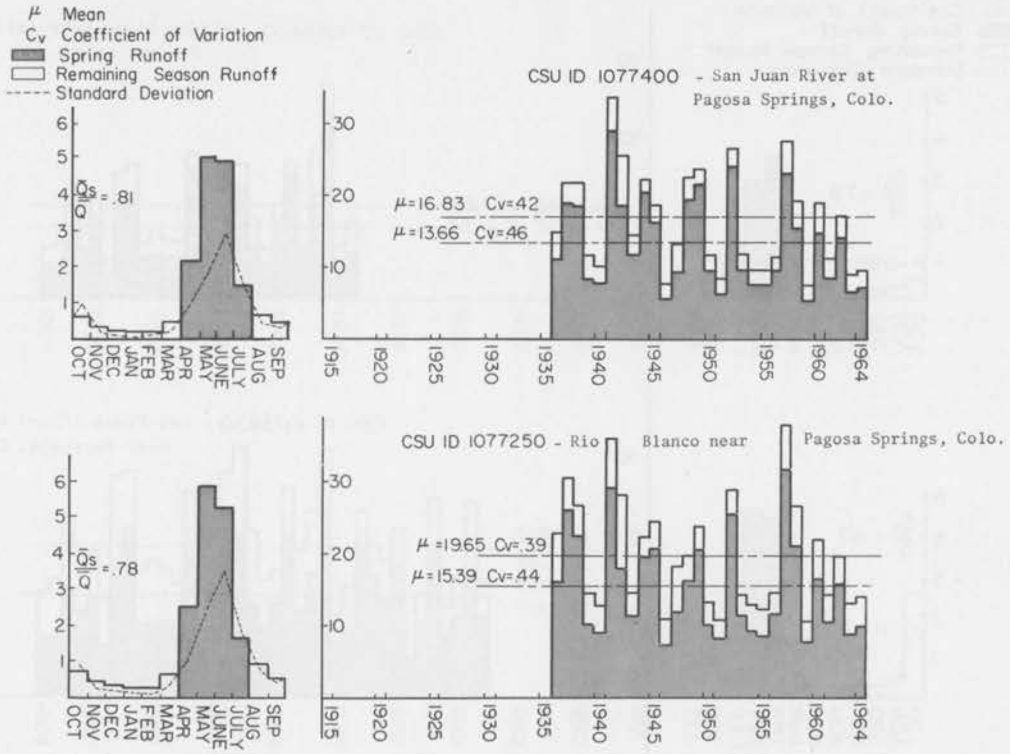

Fig. 5(e) Annual, spring, and monthly runoff (in inches) for stations San Juan River at Pagosa Springs, Colo. and Rio Blanco near Pagosa Springs, Colo. $\overline{Q}_S/\overline{Q}$ represents the ratio of mean spring runoff to mean annual runoff.

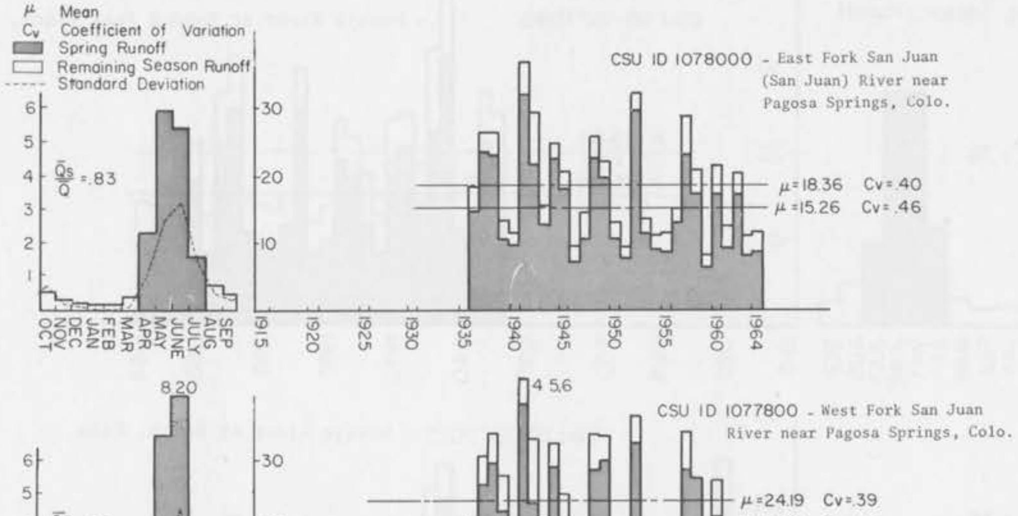

Fig. 5(f) Annual, spring, and monthly runoff (in inches) for stations East Fork San Juan (San Juan) River near Pagosa Springs, Colo. and West Fork San Juan River near Pagosa Springs, Colo. $\overline{Q}_S/\overline{Q}$ represents the ratio of mean spring runoff to mean annual runoff.

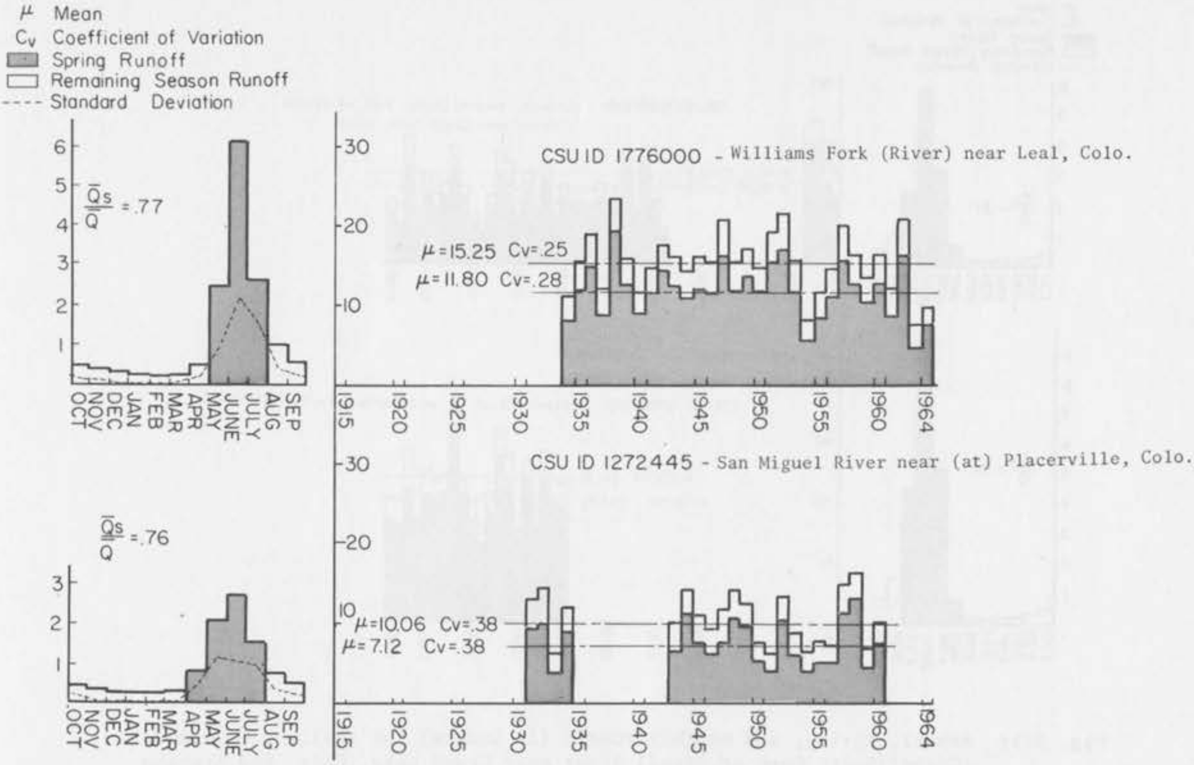

Fig. 5(g) Annual, spring, and monthly runoff (in inches) for stations Williams Fork (River) near Leal, Colo. and San Miguel River near (at) Placerville, Colo. $\overline{Q}_S/\overline{Q}$ represents the ratio of mean spring runoff to mean annual runoff.

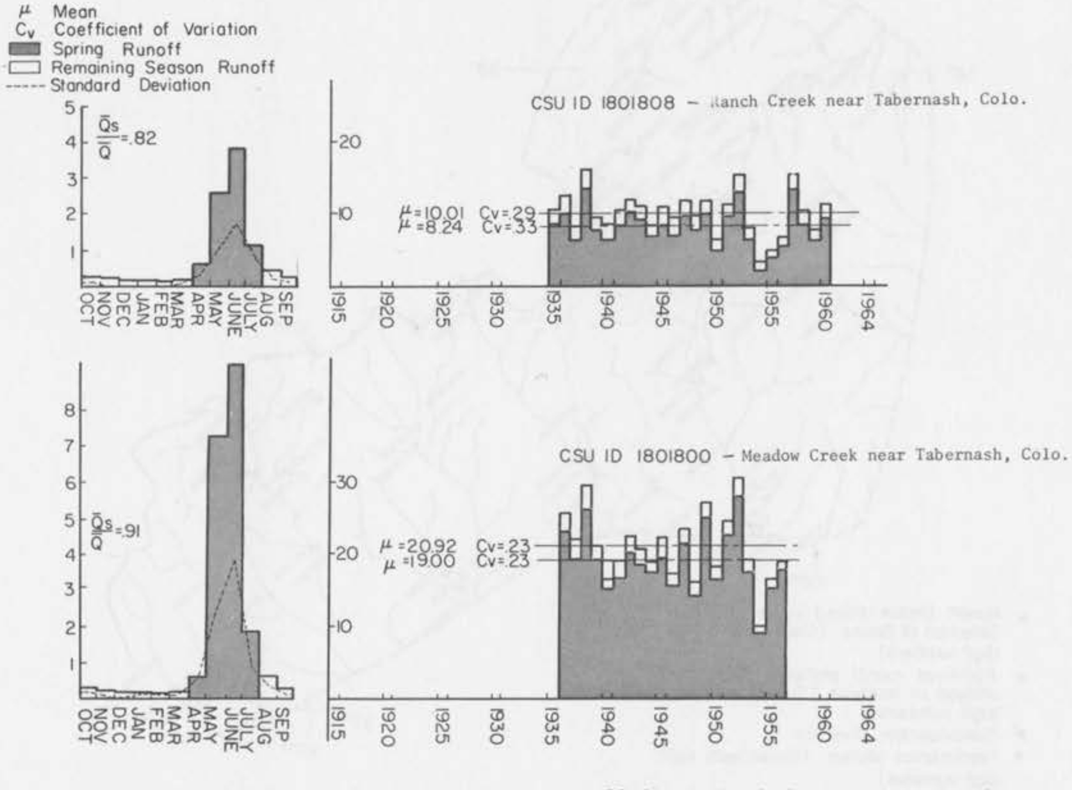

Fig. 5(h) Annual, spring, and monthly runoff (in inches) for stations Ranch Creek near Tabernash, Colo. and Meadow Creek near Tabernash, Colo. $\overline{Q}_S/\overline{Q}$ represents the ratio of mean spring runoff to mean annual runoff.

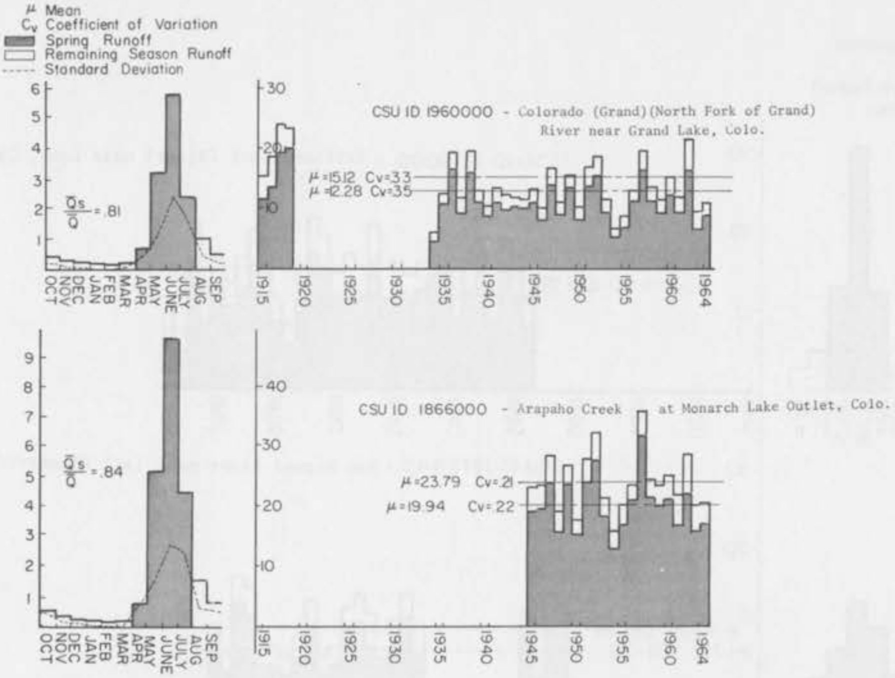

Fig. 5(i) Annual, spring, and monthly runoff (in inches) for stations Colorado (Grand)(North Fork of Grand) River near Grand Lake, Colo. and Arapaho Creek at Monarch Lake Outlet, Colo. $\overline{Q}_S/\overline{Q}$ represents the ratio of mean spring runoff to mean annual runoff.

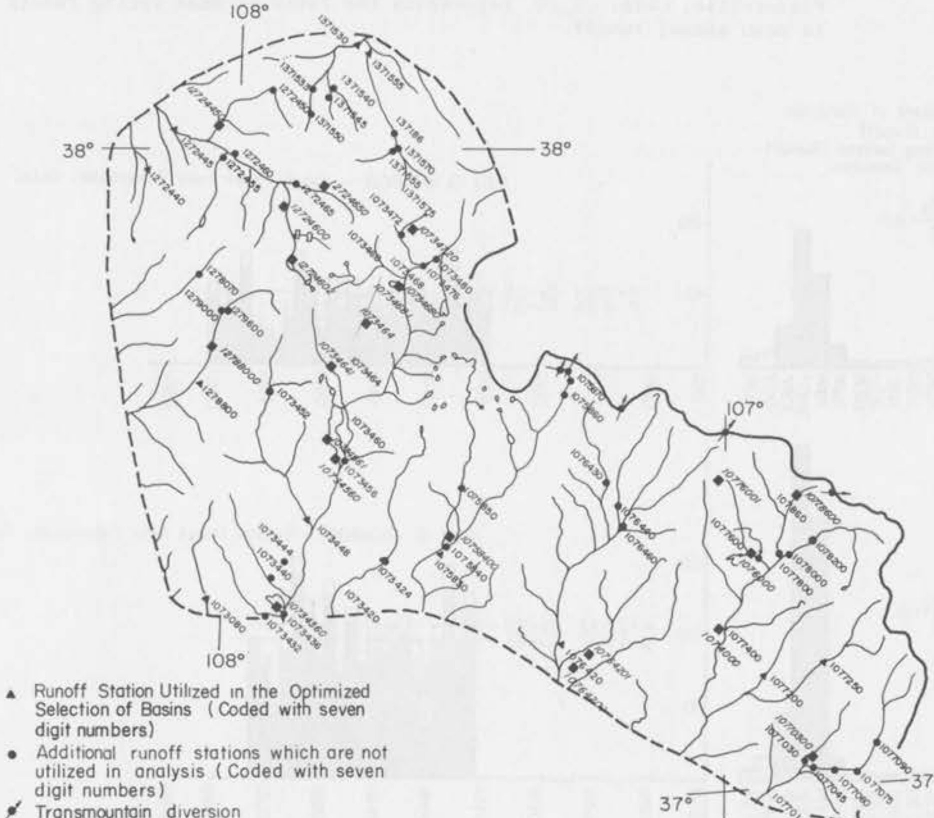

Fig. 6(a) General configuration of and location of gages within the Colorado River Basin Pilot Project area (San Juan Mountains region).

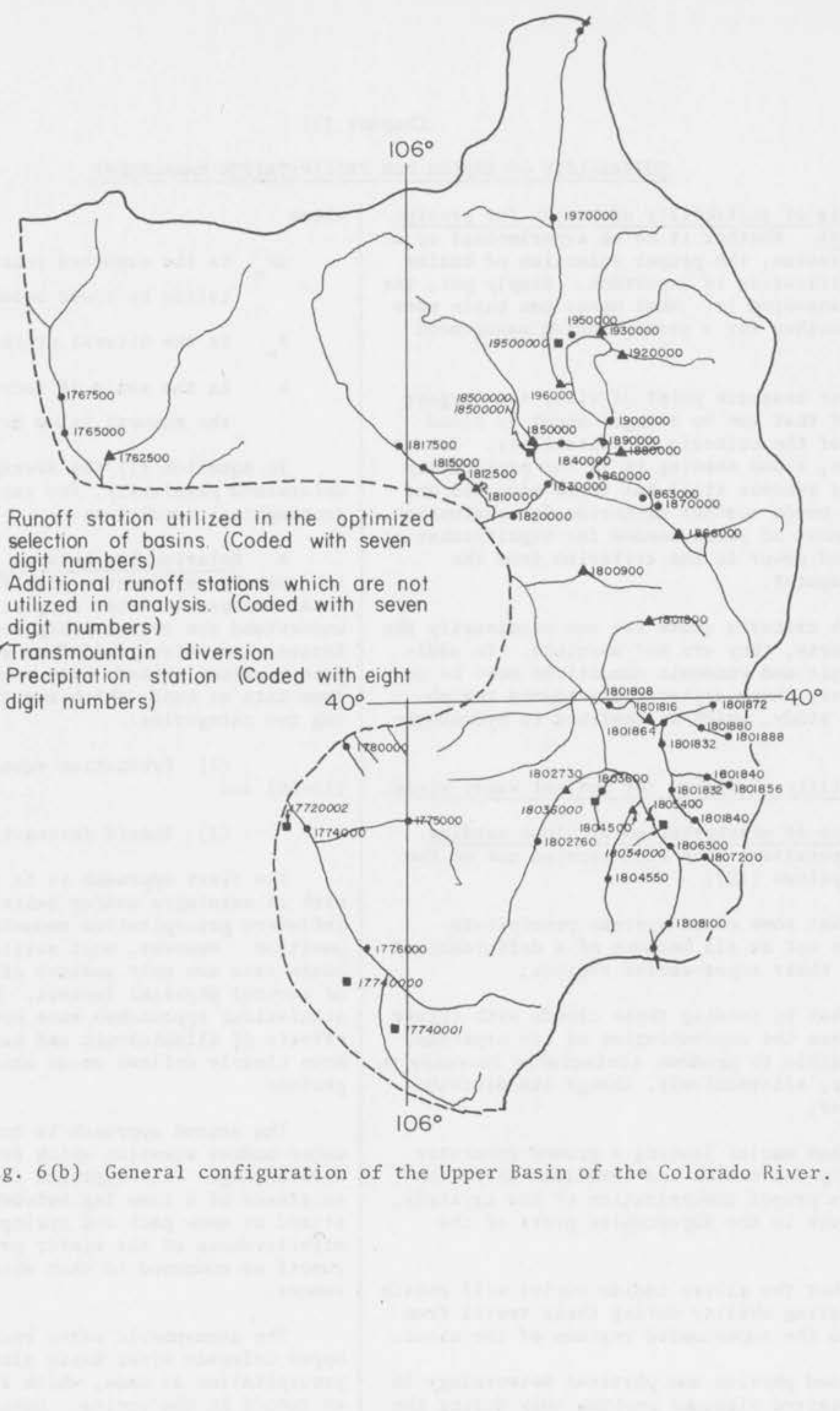

Fig. 6(b) General configuration of the Upper Basin of the Colorado River.

Chapter III

SUITABILITY OF BASINS FOR PRECIPITATION MANAGEMENT

1. Criteria of suitability of basins for precipitation management. Whether it be an experimental or a large-scale operation, the proper selection of basins for weather modification is important. Simply put, the question to be answered is: What makes one basin more suitable than another for a precipitation management operation [6]?

From a water resource point of view, the largest amount of runoff that can be brought about by cloud seeding is one of the criteria of suitability. But at the present time, cloud seeding is in the preliminary stages, and its success still has to be measured and discussed. One needs another criterion for evaluation. The smallest number of years needed for significance at a given level and power is the criterion from the evaluation standpoint.

Both of the criteria above are not necessarily the same and, of course, they are not absolute. In addition, meteorologic and economic conditions must be considered. However, these criteria are beyond the objective of this study, which is confined to hydrologic suitability.

2. Suitability of basins for optimal water yield.

a. Increase of precipitation by cloud seeding. Cloud seeding operations have been carried out on the following assumptions [12]:

(1) That some cloud systems precipitate inefficiently or not at all because of a deficiency of ice crystals in their super-cooled regions;

(2) That by seeding these clouds with silver iodide to increase the concentration of ice crystals, it might be possible to produce a detectable increase in precipitation or, alternatively, change its distribution or character;

(3) That nuclei leaving a ground generator and carried up by convection and turbulent diffusion will provide the proper concentration of ice crystals, at least somewhere in the supercooled parts of the cloud system;

(4) That the silver iodide nuclei will retain their ice nucleating ability during their travel from the generator to the supercooled regions of the cloud.

Because cloud physics and physical meteorology in general have received vigorous impetus only during the past decade principally from interest in cloud seeding, it is still difficult to predict the extent of man-made precipitation in the future. But it seems to be the consensus of opinion that present technology is not sufficiently developed to induce an additional amount of precipitation above a small percentage (10-20 percent) that occurs naturally.

At present it is a somewhat accepted opinion that the increase of precipitation by cloud seeding is proportional to the natural precipitation, i.e.,

$$\Delta P_w = k\ P_w \qquad (7)$$

where

ΔP_w is the expected increase of winter precipitation by cloud seeding,

P_w is the natural winter precipitation, and

k is the ratio of increase of precipitation to the natural value or relative increase.

In equation (7) the average value of k might be determined physically, for various meteorological and geographical conditions.

b. Relationship between runoff and precipitation. In order to implement a plan for the best use of the total manageable water supply, it is necessary to understand the relationship between climate, water losses, and water yield from watersheds. For this purpose, various methods have been developed indirectly or from data at hand, which are classified in the following two categories:

(1) Prediction equation for specific yield [13-16] and

(2) Runoff forecasting analysis [17-24].

The first approach is to relate the specific yield with climatologic and/or basin characteristics known to influence precipitation amounts, as well as their disposition. However, most available climatologic and basin data are only indices of the combined effects of several physical factors. Hence, the more complex statistical approaches have been applied. General effects of climatologic and basin characteristics are more clearly defined on an annual basis than for shorter periods.

The second approach is to find a solution to the water-budget equation which serves for water supply forecasting. This approach is based largely on the existence of a time lag between winter precipitation stored as snow pack and spring runoff and on the greater effectiveness of the winter precipitation in producing runoff as compared to that which occurs during the summer.

The atmospheric water resource project in the Upper Colorado River Basin aims to increase winter precipitation as snow, which is followed by an increase of runoff in the spring. Hence, the second approach is helpful in finding the relationship between spring runoff and winter precipitation and in estimating the increase of runoff.

c. Increase of runoff. The effect of cloud seeding is measured by the increase of usable runoff. It is assumed that runoff (Q) is a function of a representative precipitation (P). Then, in the general form,

$$Q = f(P)\ . \qquad (8)$$

But is is hard to find an integrated precipitation that represents the whole basin. Suppose that the precipitation data P_j's corresponding to Q are collected, as many as possible, in the basin in question. Equation (8) is then modified as

$$Q = f(P_1, P_2, \dots) \quad . \tag{9}$$

In the case of precipitation management in the Upper Colorado River Basin, it is the spring runoff, (Q_s), caused mainly by winter precipitation, (P_{wj}), and partially by spring precipitation, (P_{sj}), which is of concern. The relationship is represented more precisely by the following equation:

$$Q_s = f(P_{w1}, P_{s1}, P_{w2}, P_{s2}, \dots) \quad . \tag{10}$$

Multiple linear regression analysis is applied to find the approximate relationship. Finally,

$$Q_s = a + b_1 P_{w1} + c_1 P_{s1} + b_2 P_{w2} + c_2 P_{s2} + \dots \tag{11}$$

where the a, b_j, c_j are coefficients determined from available data.

Then, the increase of spring runoff, (ΔQ_s), caused by the increase of winter precipitation, (ΔP_w), is given by

$$\begin{aligned} \Delta Q_s &= (Q_s + \Delta Q_s) - Q_s \\ &= \{a + b_1(P_{w1} + \Delta P_{w1}) + c_1 P_{s1} + b_2(P_{w2} + \Delta P_{w2}) + c_2 P_{s2} + \dots\} \\ &= \{a + b_1 P_{w1} + c_1 P_{s1} + b_2 P_{w2} + c_2 P_{s2} + \dots\} \\ &= b_1 \Delta P_{w1} + b_2 \Delta P_{w2} + \dots \end{aligned} \tag{12}$$

Substituting equation (7) into (12), and averaging

$$\overline{\Delta Q}_s = b_1 k_1 \overline{P}_{w1} + b_2 k_2 \overline{P}_{w2} + \dots . \tag{13}$$

From a water resource point of view, the greater the $\overline{\Delta Q}_s$ calculated from equation (13), the more suitable the basin.

3. Suitability of basins for evaluation.

a. Two-sample u-test. One of the goals of the precipitation management program has been the rigorous establishment of the statistical significance of its attainment. For this purpose, various methods of evaluation were devised. Indeed, a great deal is already known about methods of evaluation of attainment [6].

Of course, the criteria of suitability of basins for evaluation depend upon the choice of the variable selected to test the hypothesis or the type of statistical test and upon the design of the experiments.

Assuming that the end result of seeding is to increase the natural mean, but that everything else stays the same, the criteria are derived from the two-sample u-test [6] in the following way. The two-sample u-test is a test of the hypothesis that assumes that the population mean is equal to a given value while the population standard deviation is known and stationary [25]. The statistic used in testing this hypothesis is

$$u = \frac{\overline{x} - \mu}{\sigma/\sqrt{n}} \tag{14}$$

where $\overline{x}$ is the sample mean,

μ is the population mean,

σ is the standard deviation, and

n is the sample size

with the critical region $|u| > 1.96$ if the 5 percent significance level is used. The significance of the increase in spring runoff is achieved if the observed statistic u, in equation (15), is greater than 1.96 at the 95 percent confidence level, i.e.,

$$u = \frac{\overline{\Delta Q}_s}{\sigma_{Q_s}/\sqrt{N}} \geq 1.96 \tag{15}$$

where $\overline{\Delta Q}_s$ is the expected increase in spring runoff,

N is the number of years necessary to establish the significance of the increase with a 50% power, and

σ_{Q_s} is the standard deviation of the natural spring runoff.

b. A criterion to determine the relative suitability of an individual basin. The number of years, N, necessary for evaluation is derived from equation (15)

$$N = \frac{3.84\, \sigma_{Q_s}^2}{(\overline{\Delta Q}_s)^2} \quad . \tag{16}$$

A low value of N in equation (16) provides a criterion to determine the relative suitability of many potential basins.

c. A criterion to determine the suitability of grouped basins. In the major basins there are sets of gaged sub-basins that are not, in part or in full, a tributary of any other member sub-basin of the set. Suppose that in a major basin there exist m such sub-basins. The spring runoff for each of these individual sub-basins is denoted Q_{si} $(i=1,2,\dots m)$. Now suppose one wants to choose n of the m sub-basins for a pilot program $(n < m)$. Construct a linear combination of Q_{si}'s, i.e.,

$$Q_s^* = \alpha_1 Q_{s1} + \alpha_2 Q_{s2} + \dots + \alpha_n Q_{sn} = \sum_{i=1}^{n} \alpha_i Q_{si} \quad . \tag{17}$$

The variance of Q_s^* is given by

$$\sigma_{Q_s^*}^2 = \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} \alpha_i \alpha_j \tag{18}$$

where

$$a_{ij} = \begin{cases} \sigma^2_{Q_{si}} & \text{for } i=j \\ \mathrm{Cov}(Q_{si}, Q_{sj}) & \text{otherwise.} \end{cases} \qquad (19)$$

The increase of spring runoff from grouped basins, ΔQ^*_s, is given by

$$\Delta Q^*_s = \alpha_1 \Delta Q_{s1} + \alpha_2 \Delta Q_{s2} + \ldots + \alpha_n Q_{sn} = \sum_{i=1}^{n} \alpha_i \Delta Q_{si}, \qquad (20)$$

where ΔQ_{si} $(i=1,2,\ldots,n)$ represents the increase in spring runoff from an individual basin. Now impose the restriction that

$$\overline{Q}^*_s = \sum_{i=1}^{n} \alpha_i \overline{Q}_{si} = \sum_{i=1}^{n} \overline{Q}_{si} \qquad (21)$$

where $\overline{Q}^*_s$ is the mean of the Q^*_s values and $\overline{Q}_{si}$ is the mean of the Q_{si} values. Also impose the restriction that $\overline{\Delta Q}^*_s$ is equal to the sum of the $\overline{\Delta Q}_{si}$ values, i.e.,

$$\overline{\Delta Q}^*_s = \sum_{i=1}^{n} \alpha_i \overline{\Delta Q}_{si} = \sum_{i=1}^{n} \overline{\Delta Q}_{si} \ . \qquad (22)$$

Finally the number of years, N*, for evaluation of grouped basins is given by the following expression:

$$N^* = \frac{3.84 \sigma^2_{Q^*_s}}{(\overline{\Delta Q}^*_s)^2} = \frac{3.84 \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} \alpha_i \alpha_j}{(\overline{\Delta Q}^*_s)^2} \propto \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} \alpha_i \alpha_j \qquad (23)$$

where the α_i and α_j are as yet arbitrary but subject to the constraints expressed by equations (21) and (22). Choose the α_i's such that the number of years, N*, is kept to a minimum value. Setting

$$f(\alpha_1, \alpha_2, \ldots, \alpha_n) = \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} \alpha_i \alpha_j$$

$$g_1(\alpha_1, \alpha_2, \ldots, \alpha_n) = \sum_{i=1}^{n} (\overline{Q}_{si} \alpha_i) - \left(\sum_{i=1}^{n} \overline{Q}_{si} \right)$$

$$g_2(\alpha_1, \alpha_2, \ldots, \alpha_n) = \sum_{i=1}^{n} (\overline{\Delta Q}_{si} \alpha_i) - \left(\sum_{i=1}^{n} \overline{\Delta Q}_{si} \right)$$

a new function is defined

$$F(\alpha_1, \alpha_2 \ldots, \alpha_n, \lambda_1, \lambda_2) = f(\alpha_1, \alpha_2, \ldots, \alpha_n) - \lambda_1 g_1(\alpha_1, \alpha_2, \ldots, \alpha_n) - \lambda_2 g_2(\alpha_1, \alpha_2, \ldots \alpha_n) \ . \qquad (24)$$

The α_i's that make the objective function $F(\alpha_1, \alpha_2, \ldots, \alpha_n)$ in equation (24) minimum give the minimum value for N* in equation (23).

By taking the partial derivative of $F(\alpha_1, \alpha_2, \ldots \alpha_n, \lambda_1, \lambda_2)$ with respect to the α_i's, λ_1, and λ_2 and setting each derivative equal to zero, one obtains the system of equations:

$$\frac{\partial F}{\partial \alpha_k} = \sum_{j=1}^{n} a_{kj} \alpha_j + \sum_{i=1}^{n} a_{ik} \alpha_i - \lambda_1 \overline{Q}_{sk} - \lambda_2 \overline{\Delta Q}_{sk}$$

$$= 2 \sum_{i=1}^{n} a_{ki} \alpha_i - \overline{Q}_{sk} \lambda_1 - \overline{\Delta Q}_{sk} \lambda_2 = 0$$

for k = 1,2,..,n

$$\frac{\partial F}{\partial \lambda_1} = - \sum_{i=1}^{n} \overline{Q}_{si} \alpha_i + \left(\sum_{i=1}^{n} \overline{Q}_{si} \right) = 0$$

$$\frac{\partial F}{\partial \lambda_2} = - \sum_{i=1}^{n} \overline{\Delta Q}_{si} \alpha_i + \left(\sum_{i=1}^{n} \overline{\Delta Q}_{si} \right) = 0$$

or in matrix notation

$$\begin{bmatrix} 2a_{11} & 2a_{12} & \cdots\cdots & 2a_{1n} & -\overline{Q}_{s1} & -\overline{\Delta Q}_{s1} \\ 2a_{21} & 2a_{22} & \cdots\cdots & 2a_{2n} & -\overline{Q}_{s2} & -\overline{\Delta Q}_{s2} \\ \vdots & \vdots & & \vdots & \vdots & \vdots \\ 2a_{n1} & 2a_{n2} & \cdots\cdots & 2a_{nn} & -\overline{Q}_{sn} & -\overline{\Delta Q}_{sn} \\ \overline{Q}_{s1} & \overline{Q}_{s2} & \cdots\cdots & \overline{Q}_{sn} & 0 & 0 \\ \overline{\Delta Q}_{s1} & \overline{\Delta Q}_{s2} & \cdots\cdots & \overline{\Delta Q}_{sn} & 0 & 0 \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_n \\ \lambda_1 \\ \lambda_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ \left(\sum_{i=1}^{n} \overline{Q}_{si} \right) \\ \left(\sum_{i=1}^{n} \overline{\Delta Q}_{si} \right) \end{bmatrix} \qquad (25)$$

The system of equation (25) is linear and its resolution for the unknown α_i's is obtained by the Gaussian elimination procedure. Thus a procedure is described that objectively selects the optimal group of basins of a given size among a larger set. The procedure also determined the optimal parameters of the combination of runoff variables for minimum time evaluation.

It remains to apply this technique in practice to the Upper Colorado River Basin. Before doing so, Chapter IV describes the data used in the analysis.

Chapter IV

DATA USED FOR THIS STUDY

The data used in this study are winter and spring precipitation and spring runoff. They have to be collected in a certain order and have to satisfy specific criteria. These conditions are discussed in this chapter.

1. Precipitation and runoff in the Upper Colorado Basin.

a. Precipitation records. According to the United States Weather Bureau's "Substation History" (26-30), about 400 stations are found in the Upper Colorado River Basin, including stations with records of storage gage and stations not now in operation. For 312 of these stations, monthly precipitation data were collected from the following sources and recorded on magnetic tapes.

(1) The United States Weather Bureau, "Climatological Data" [31,35]

(2) The United States Weather Bureau, "Climatic Summary of the United States" [36-37]

(3) The United States Weather Bureau, "Climatography of the United States" [38]

(4) The United States Weather Bureau, "Monthly Weather Review" [39]

(5) The United States Department of Agriculture, "Report of the Chief of Weather Bureau" [40]

The characteristics of the precipitation stations are tabulated in Appendix A.

b. Runoff records. As a part of Colorado State University hydrology data system, monthly runoff records have been collected and recorded on magnetic tapes [6,9]. The source of the data is the United States Geological Survey, "Water Supply Papers" [41]. The total number of stations from which data were collected is 749.

c. Hydrologic data system. There is no relationship between the numbering system of runoff stations of the United States Geological Survey and that of precipitation stations of the United States Weather Bureau. For fast data processing and particularly for ease of correlation between precipitation and runoff, it is desirable to have identical or almost identical identification numbers for neighboring precipitation and runoff stations for the entire Upper Colorado River Basin. The Colorado State University numbering system was developed for this purpose:

(1) Runoff stations are coded with seven digit numbers. Runoff stations within the same drainage have an intermediate number between two limiting numbers that characterize the downstream and upstream reach of the drainage area [6].

(2) Precipitation stations are coded with eight digit numbers. The first seven digits are identical to the Colorado State University identification number of the nearest downstream runoff station. However, in some areas there may be several precipitation gages close to a single runoff station. The eighth digit in the station number makes it possible to distinguish between the gages in this situation. The precipitation station closest to the associated runoff station is assigned a zero for its eighth digit. The precipitation station next in proximity is assigned one for its eight digit, and so forth.

2. The accuracy of data measurements.

It is well known that the observed precipitation does not necessarily represent the true amount of water that falls over a station or over the surrounding area [42]. However, the precipitation data that correlate highly with runoff data are still useful indices in this study.

3. Non-homogeneity and inconsistency of records.

Non-homogeneity and inconsistency of precipitation data are introduced when there is a change in location, exposure, or instrument. Substation History [26-30] and Climatological Data [31-35], both published by the Weather Bureau, show horizontal movement and elevation change. However, the environment and local orography cannot be shown.

Most of the drainage area in the Upper Colorado River Basin has been subjected to transmountain diversion, transbasin diversion, interbasin diversion, regulation by reservoir, and irrigation diversion that causes a non-homogeneity in the runoff data. The information about the first four cases is given in the Water Supply Papers [41] and is used for correction of runoff data on the monthly level [9]. As to irrigation diversion, there is no available record. Furthermore, it is very difficult to estimate seasonable consumptive use and return rate to river. In the high mountain regions, the irrigation allotment is small in amount and is diverted mainly in summer. Correction for irrigation diversion is not done for this reason.

4. Filling missing data.

It is necessary to establish a reliable connection between stations having incomplete records and those that are complete. This is done by estimating the missing data from nearby stations with records covering the missing months and having a sufficiently long record which coincides with that of the station with incomplete records. In this study, a simple linear regression method is applied for this purpose.

Chapter V

DATA PROCESSING AND RESULTS

The techniques described in Chapter III are applied by using the data discussed in Chapter IV. The goal of this chapter is to determine the relative suitability of individual basins within the Upper Colorado River Basin and to select the favorable combinations of sub-basins in the two pilot areas.

1. Mean winter precipitation and mean spring runoff.

a. Seasonal and yearly variability of precipitation. The mean and standard deviations of monthly precipitation are computed for 10 stations in the pilot area and are plotted on Fig. 4. The annual and winter precipitation time series are also shown in the same figures. The distribution of monthly precipitation is roughly uniform, on the average, though there are peaks in July and August and a low in June. The coefficients of variation of monthly precipitation are very large though those of annual precipitation are relatively small. The ratios of winter to annual precipitation are around 0.6.

b. Seasonal and annual variability of runoff. The mean and standard deviations of monthly runoff were computed for 18 stations in the pilot areas and are plotted on Fig. 5. The annual and spring runoff time series are also shown in the same figures. These figures illustrate the typical behavior of stations located at a high altitude. An outstanding rise during April through June, a decline in July and August, and steady flow in fall and winter are common to all the watersheds.

Precipitation appears as snow during October through April. During this season, the watersheds are covered with snow and the streams are frozen. As the weather warms up in the spring, the snow pack on the high mountains begins to melt and pours into the streams along with the runoff from spring precipitation. The precipitation that falls during the summer season is stored in the soil, but strong evapotranspiration takes place and summer precipitation does not contribute to runoff to a great extent. This is why runoff displays an extreme seasonal variability compared to the nearly uniform distribution of seasonal precipitation. For this reason, the coefficients of variations of both annual and spring runoff are high for all the stations.

c. Mean winter precipitation. As far as precipitation management in the Upper Colorado River Basin is concerned, mostly the winter precipitation is significant in the application of artificial techniques. As discussed in Section 2 of Chapter III the increase of precipitation is roughly proportional to the natural precipitation. The establishment of zones of equal winter precipitation was attempted over the Upper Colorado River Basin. Though it is desirable to obtain recording years common to all the stations, all those having records of five years or more were used. Figure 7 shows isohyets of 5, 7.5 and 10 inches (very rough and uncorrected for topography).

The names of the watersheds that have a great amount of winter precipitation follow in order:

(1) San Juan Mountains

(2) Upper basin of the Colorado River

(3) Upper reach of the Yampa River and its tributaries

(4) Headwaters of the Rafael River

(5) Upper basins of Uinta River, Lake Fork, and Rock Creek.

d. Mean spring runoff. The increase of precipitation in winter appears as spring runoff. The spring runoff might be a rough indicator for optimal water yield.

Lines of equal spring runoff were drawn and are depicted in Fig. 8. The streams having a great amount of spring runoff, of course, correspond to the watersheds with a large amount of winter precipitation.

2. Relation between precipitation and runoff.

a. Stepwise multiple regression. To determine the coefficients a, b_i, and c_i in equation (11), stepwise multiple regression was used. Its chief advantage is to produce an equation that uses only a small number of prediction variables and that has a comparatively high coefficient of determination [43].

b. Correlation between winter and spring precipitation. For all precipitation stations in the pilot areas the correlation coefficient between winter and spring precipitation was calculated. Table 1 shows no correlation.

TABLE 1 CORRELATION COEFFICIENT, (r), BETWEEN WINTER AND SPRING PRECIPITATION

CSU ID	r
10734360	.04
10734560	.12
10734641	.17
10774000	.30
10778600	.01
12724450	-.04
12724602	-.32
13715600	.58
18036000	-.24
18054000	-.06
18500000	.26
19500000	.24

c. Watershed without precipitation station data available. Though it would be of interest to study the watersheds in the high altitudes, generally there are few, if any, stations there. In this case data from one of the precipitation stations nearby were used to compute the coefficients in equation (11). As long as a good correlation exists, a sufficient forecasting equation can be found.

d. Computation and results. Computation was done for all possible sets of precipitation and runoff having

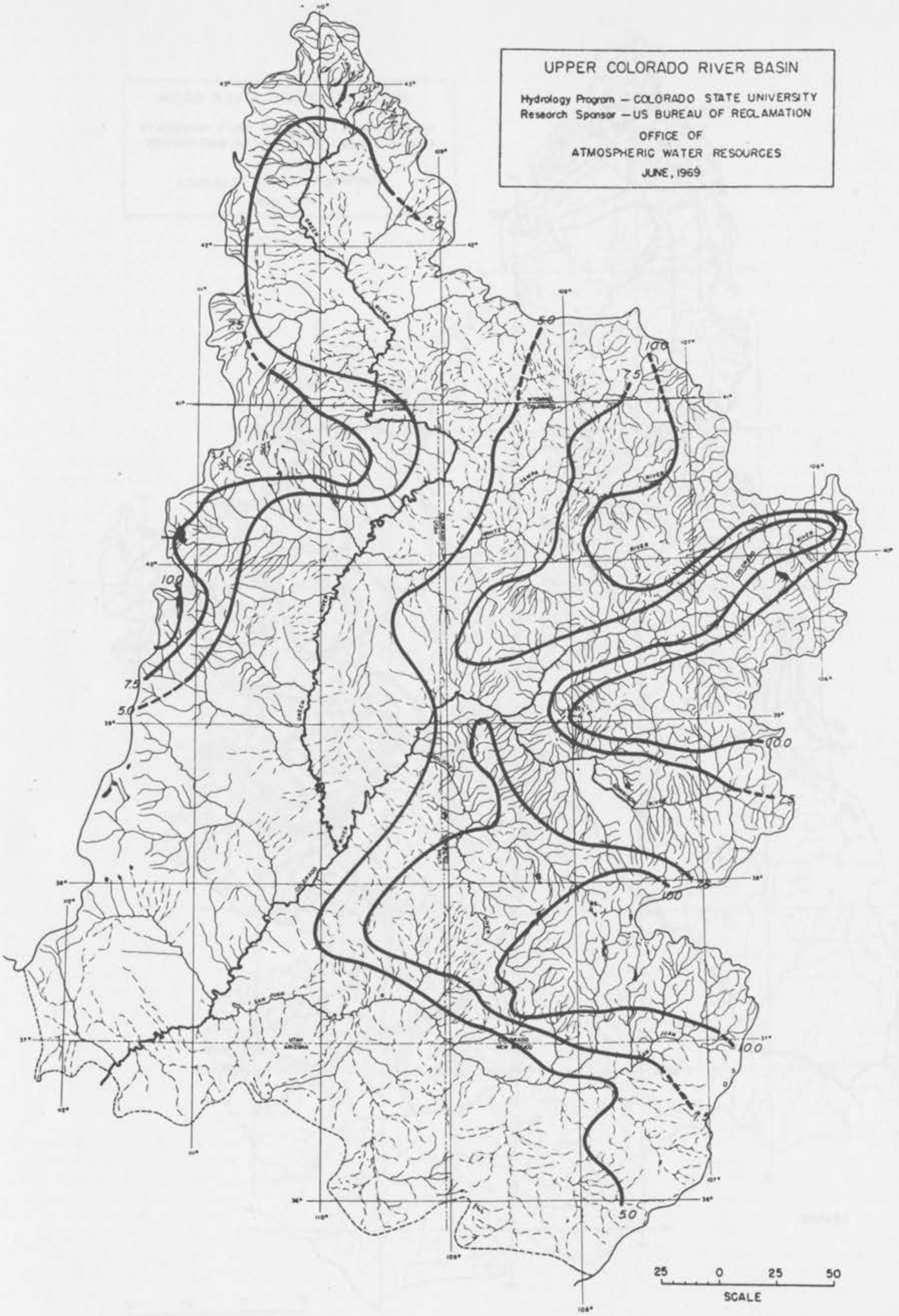

Fig. 7 Mean winter precipitation (in inches)

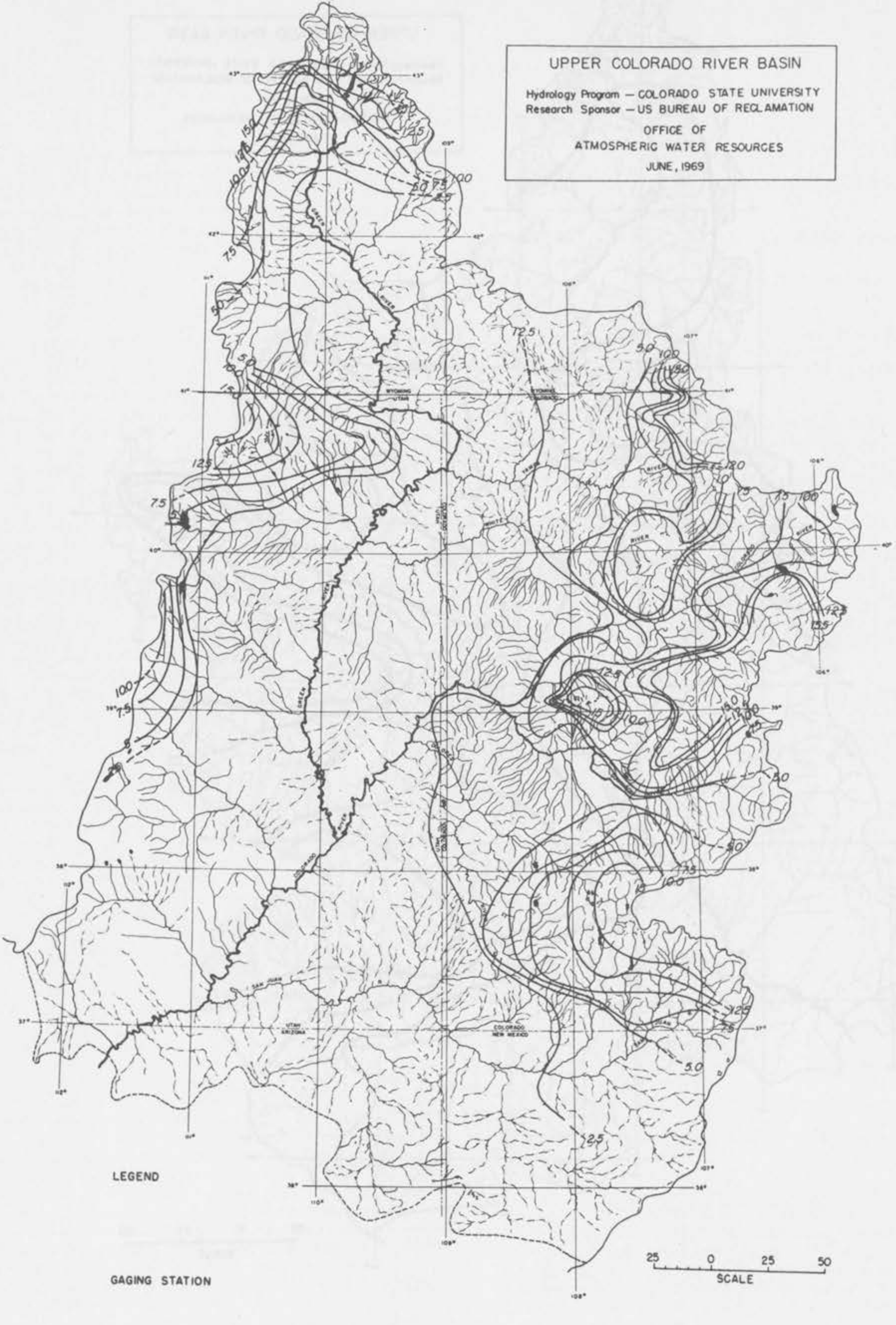

Fig. 8 Mean spring runoff (in inches)

a common recording length. Three hundred and sixty-five sets of these with greater than 0.90 correlation coefficient were used for the calculation of the increase in runoff and of the number of years needed for evaluation (see Appendix B).

3. Increase of runoff. At the present stage, it is impossible to assign scientifically a reasonable value to the relative increase in precipitation, k_i, in equation (7), for each station. A uniform 10 percent increase of winter precipitation over its natural value is assumed for further computation. Then the increase of spring runoff induced by an increase of winter precipitation is, on the average, found from equation (13) in Section 2 of Chapter III.

Here the $\overline{P}_{wi}$ were calculated, not for the common recording length, which was used to find the regression line, but for the whole recording length of each station (see Appendix B).

The computed value of $\overline{\Delta Q}_s$ for every station is plotted on Fig. 9 and rough contour lines of equal increase of spring runoff are shown there.

The names of the watersheds where the greatest increase in runoff is expected follow:

(1) San Juan Mountains,

(2) Upper reach of the Yampa River and its tributaries,

(3) Headwaters of the Green River,

(4) Upper basin of the Colorado River,

(5) Upper basins of Uinta River, Lake Fork, and Rock Creek, and

(6) Headwaters of the Rafael River basin.

These watersheds also have a large amount of natural precipitation and natural spring runoff.

4. Number of years needed for evaluation. Using $\overline{\Delta Q}_s$ calculated in the previous section, the number of years needed for evaluation was computed for each station by equation (16) in Section 3 of Chapter III.

The results are shown in Appendix B and on Fig. 10. The occurrence of aberrant values made it difficult to draw more precise contour lines. This is caused mainly by the fact that the common recording length was not used, and the variability of the data affects the value of N to the second power, compared to the case of $\overline{\Delta Q}_s$ in equation (13).

In general, the value of N are smaller in the high mountain watersheds where the large increase of spring runoff is expected. However, when the size of the watershed becomes quite small the trend sometimes reverses. This seems to occur to the watersheds consisting of sub-basins with different hydrological features and with a smaller variance. The names of the watersheds where the smaller number of years can be expected follow:

(1) Upper reach of the Yampa River and its tributaries,

(2) Headwaters of the Green River,

(3) Upper basin of the Colorado River,

(4) Upper basins of Uinta River, Lake Fork, and Rock Creek, and

(5) San Juan Mountains.

5. Optimized selection of basins in the pilot area.

(a) Runoff stations in the pilot area. Out of 53 stations in the San Juan Mountains and 49 stations in the upper basin of the Colorado River, 15 and 14 stations, respectively, were selected for the study. They gage representative sub-basins and have relatively long records. The locations of the stations and their characteristics are found in Table 2, and on Figs. 6 and 11. The covariance matrix was computed and is shown in Table 3.

(b) Optimized selection of basins. As discussed in Section 3 of Chapter III an attempt was made to find a combination of numbers of sub-basins giving the minimum number of years for evaluation. This was accomplished by solving equation (19) for all possible combinations of two through six stations out of 15 in the San Juan Mountains and out of 14 in the upper basin of the Colorado River. The number of all possible combinations is so large that only those combinations which yield the twenty lowest values of N^* are plotted. In Fig. 12, N^* is plotted versus the increase of spring runoff and also versus the drainage area. The minimum value in the San Juan Mountains is six and in the upper basin of the Colorado River it is three.

The same calculation was performed setting all the α_i's equal to 1 in equation (17) instead of optimizing the parameters. The results are shown on Fig. 12. The comparison of the results for the two cases demonstrate that the method is effective.

The analysis of the results indicates that several particular sub-basins play a particular important role in making N^* small. They are in:

(a) the San Juan Mountains

1077015	Navajo River at Edith
1077250	Rio Blanco near Pagosa Springs
1371555	Uncompahgre River near Ridgway,

and in

(b) the upper basin of the Colorado River

1762500	East Fork Troublesome Creek near Troublesome
1810000	Willow Creek below Willow Creek Reservoir
1930000	North Inlet at Grand Lake.

These stations do not necessarily have a small value of N in Table 2. Table 4 list the optimal combination of gages for group sizes equal to 2, 3, 4, 5 and 6 selected from 15 stations in the San Juan Mountains and from 14 stations in the upper basin of the Colorado River.

The results are very encouraging for evaluation of the pilot projects. The method of optimized grouping of basins brings a very large reduction in the number of years needed to establish significance. One may nevertheless question the method. In other words how sensitive is the method? Could a slight variation in this or that parameter say double the calculated value of N^*, quadruple it ... etc?

A complete theoretical answer to the question is not easy. One can however obtain an idea by varying various

Fig. 9 Expected increase in spring runoff due to a uniform 10% increase in winter precipitation (in inches)

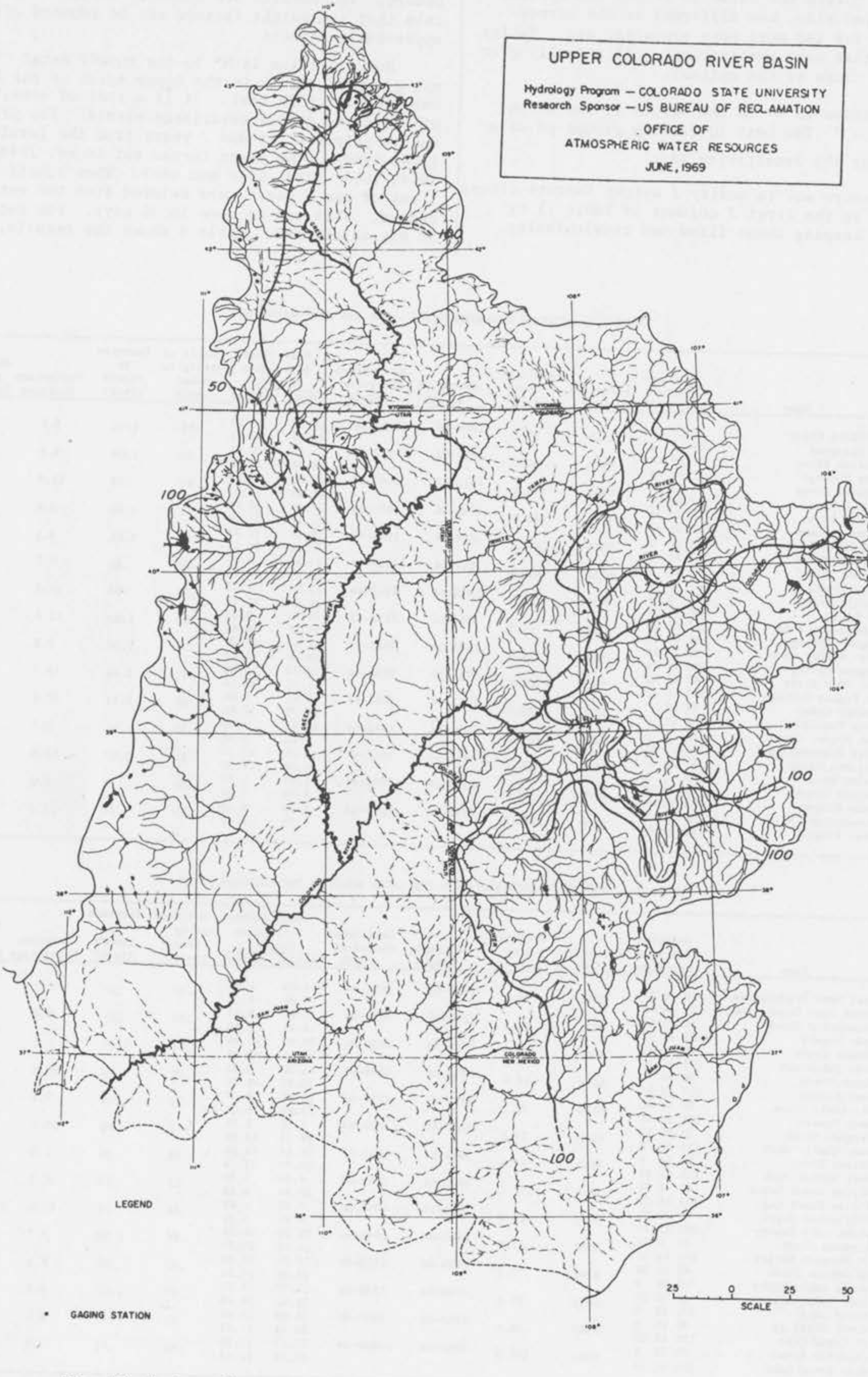

Fig. 10 Number of years needed for evaluation (based on the two-sample u-test)

parameters and observing the changes in the calculated values of N*. Given the value of N* for the optimal group of a given size, how different is the corresponding value for the next best grouping, etc. Tables 5 and 6 show that many combinations will actually give a value of N* close to the optimal.

How sensitive is N* to the values of the weight coefficients α_i? The best 10 ranking groups of size 6 were used for the sensitivity test.

The procedure was to modify 2 weight factors (those corresponding to the first 2 columns of Table 7) by 1, 5 and 10%, keeping these fixed and recalculating the remaining $4\alpha_i$ according to the optimization procedure. The results are shown in Table 7. They indicate that the weight factors can be rounded off without appreciable effects.

How sensitive is N* to the runoff data? The optimal group of size 6 in the Upper Basin of the Colorado was used for this test. It is a test of sensitivity of N* to the sample covariance matrix. The procedure was to select at random 7 years from the total record (1948-1964). The years turned out to be: 1948, 1951, 1954, 1956, 1958, 1960 and 1963. Then runoff data for 3 out of the 7 years were deleted from the entire record. This can be done in 35 ways. For each sample N* was calculated. Table 8 shows the results.

TABLE 2(a) STATION CHARACTERISTICS - THE SAN JUAN MOUNTAINS

CSU ID (U.S.G.S. No.)	Name	Location Latitude Longitude	Elevation feet	Drainage Area mile^2	Recording Length	Continuous Recording Length	Mean (inch) & variance (inch^2)		Ratio of spring to annual runoff	Increase in runoff (inch)	Percentage Increase	Number of years for Evaluation
							Annual	Spring				
1073080 (9.36550)	La Plata River at Hesperus	37 17 20 108 2 5	8105	37.0	1904-64	1917-64	16.70 45.03	13.50 42.81	.81	1.15	8.5	124
1073420 (9.3630)	Florida River near Durango	37 19 40 107 44 40	7302	96.0	1899-60	1927-60	15.13 46.03	12.21 27.39	.81	1.00	8.2	105
1073448 (9.36100)	Hermosa Creek near Hermosa	37 25 30 107 50 20	6706	172.0	1912-64	1940-64	10.95 28.25	8.91 17.53	.81	.98	11.0	70
1073460 (9.35950)	Animas River above Tacoma	37 34 10 107 46 40	7520	348.0	1946-56	1946-56	20.66 45.12	15.91 39.95	.77	1.50	9.4	68
1075830 (9.35350)	Los Pinos River near Bayfield	37 23 0 107 34 30	7515	284.0	1928-64	1928-64	18.55 37.46	12.47 30.11	.67	1.01	8.1	113
1076420 (9.34950)	Piedra River near Piedra	37 14 0 107 20 30	6530	371.0	1912-64	1939-64	11.46 31.16	9.02 18.71	.79	.88	9.7	93
1077015 (9.34600)	Navajo River at Edith	37 0 10 106 54 25	7033	172.0	1913-64	1913-64	12.46 24.65	9.37 13.70	.75	.94	10.0	60
1077200 (9.34350)	Rito Blanco near Pagosa Springs	37 11 40 106 54 20	7330	23.3	1935-52	1935-52	10.74 35.33	9.43 19.81	.88	1.02	11.8	73
1077250 (9.34300)	Rio Blanco near Pagosa Springs	37 12 46 106 47 38	7950	58.0	1935-64	1935-64	19.65 59.20	15.39 46.42	.78	1.31	8.5	104
1077400 (9.34250)	San Juan River at Pagosa Springs	37 15 50 107 0 40	7052	298.0	1911-64	1935-64	16.83 51.86	13.66 38.54	.81	1.46	10.7	69
1272440 (9.17300)	Beaver Creek near Norwood	37 58 0 108 11 0	8008	35.2	1942-64	1963-64	6.55 35.73	5.46 17.89	.83	1.14	20.9	53
1272445 (9.17250)	San Miquel Creek near Placerville	38 2 5 108 7 15	7096	308.0	1909-64	1942-64	10.06 9.66	7.39 8.49	.73	.56	7.5	104
1278800 (9.16500)	Dolores River below Rico	37 38 25 108 3 5	8422	105.0	1952-64	1952-64	16.44 46.04	13.57 14.39	.83	1.57	11.6	22
1371530 (9.14700)	Dallas Creek near Ridgway	38 10 50 107 45 40	6980	96.2	1922-64	1956-64	5.47 4.74	2.94 2.41	.54	.24	7.9	161
1371555 (9.14620)	Uncompahgre River near Ridgway	38 11 5 107 44 40	6878	150.0	1959-64	1959-64	13.49 3.09	9.19 4.10	.68	1.16	12.6	12

TABLE 2(b) STATION CHARACTERISTICS - THE UPPER BASIN OF THE COLORADO RIVER

CSU ID (U.S.G.S. No.)	Name	Location Latitude Longitude	Elevation feet	Drainage Area mile^2	Recording Length	Continuous Recording Length	Mean (inch) & variance (inch^2)		Ratio of spring to annual runoff	Increase in runoff (inch)	Increase Percentage	Number of years for Evaluation
							Annual	Spring				
1762500 (9.0400)	East Fork Troublesome Creek near Troublesome	40 9 27 106 16 58	7750	76.0	1937-64	1954-64	4.95 4.46	4.04 4.32	.82	.31	7.7	173
1800900 (9.0355)	Strawberry Creek near Granby	40 5 10 105 49 30	8650	12.6	1936-45	1936-45	6.92 4.57	5.71 3.90	.83	.51	8.9	57
1801800 (9.0330)	Meadow Creek near Tabernash	40 2 55 105 46 30	9780	7.0	1936-56	1936-56	20.92 23.66	19.00 65.24	.91	1.39	7.3	181
1801816 (9.0320)	Ranch Creek near Fraser	39 57 0 105 45 54	8670	19.9	1934-64	1934-64	11.30 26.92	8.98 26.92	.80	.65	16.3	245
1802730 (9.0265)	St. Louis Creek near Fraser	39 54 30 105 52 45	8980	32.8	1934-64	1934-64	12.99 19.95	9.27 16.18	.71	.66	7.1	143
1804500 (9.0250)	Vasquez Creek near Winter Park	39 55 13 105 47 5	8769	27.8	1907-64	1934-64	7.10 24.21	5.05 12.00	.71	.75	14.9	81
1805400 (9.0240)	Frazer River near Winter Park	39 54 0 105 46 35	8900	27.6	1911-64	1911-64	14.84 64.70	10.99 23.74	.74	.26	2.4	1349
1810000 (9.0210)	Willow Creek below Willow Creek Res.	40 8 45 105 56 22	8024	134.0	1953-64	1953-64	4.08 10.84	2.72 6.39	.67	.55	20.2	81
1850000 (9.0180)	Stillwater Creek above Lake Granby	40 11 20 105 53 40	8310	18.8	1950-56	1950-56	7.45 9.35	6.42 3.24	.86	.85	13.3	17
1866000 (9.0165)	Arapaho Creek at Monarch Outlet	40 6 45 105 44 57	8310	47.1	1945-64	1945-64	23.79 24.78	19.94 22.98	.84	1.52	7.7	38
1880000 (9.0155)	Columbine Creek above Lake Granby	40 11 20 105 49 0	8282	7.3	1950-56	1950-56	12.56 22.39	10.36 88.21	.83	.95	9.2	375
1920000 (9.0135)	East Inlet near Grand Lake	40 14 20 105 48 0	8371	27.1	1948-56	1948-56	21.77 26.62	18.83 29.28	.87	1.57	8.3	46
1930000 (9.0115)	North Inlet at at Grand Lake	40 15 0 105 49 50	8380	46.6	1950-56	1950-56	19.99 30.44	16.89 17.31	.84	1.36	8.1	36
1960000 (9.0110)	Colorado River near Grand Lake	40 13 8 105 51 25	8380	103.0	1904-64	1934-64	15.17 25.34	12.28 12.11	.81	.92	7.5	55

TABLE 3 COVARIANCE MATRIX (Calculated for data within the period 1948 - 1964)

(a) The San Juan Mountains

CSU ID	1073080	1073420	1073448	1073460	1075830	1076420	1077015	1077200	1077250	1077400	1272440	1272445	1278800	1371530	1371555
1073080	40.30	31.28	24.93	37.18	31.87	25.39	22.28	23..1	39.75	36.61	23.74	16.00	36.39	6.05	23.92
1073420	31.28	27.21	20.85	31.51	27.48	21.69	17.42	19.02	30.35	30.27	19.16	13.57	29.98	5.08	19.96
1073448	24.93	20.85	16.53	24.56	21.14	16.88	14.02	15.22	24.31	23.54	15.38	10.68	23.72	3.93	15.68
1073460	37.18	31.51	24.56	37.69	32.08	25.32	21.26	22.82	37.40	35.83	23.66	16.32	36.09	6.09	23.72
1075830	31.87	27.48	21.14	32.08	28.40	22.08	17.94	19.64	31.81	31.30	19.54	13.49	30.75	5.14	19.90
1076420	25.39	21.69	16.88	25.32	22.08	17.65	14.24	15.50	24.69	24.79	15.47	10.65	24.28	3.91	15.63
1077015	22.28	17.42	14.02	21.26	17.94	14.24	12.94	13.66	23.15	20.63	14.16	9.20	20.94	3.42	13.62
1077200	23.71	19.02	15.22	22.82	19.64	15.50	13.66	15.00	24.48	22.36	14.82	9.94	22.34	3.65	14.81
1077250	39.75	30.35	24.31	37.40	31.81	24.69	23 15	24.48	43.78	37.31	24.78	16.10	37.38	6.39	24.66
1077400	36.61	30.27	23.54	35.83	31.30	24.79	20.63	22.36	37.31	36.38	21.84	14.67	34.75	5.57	22.12
1272440	23.74	19.16	15.38	23.66	19.54	15.47	14.16	14.82	24.78	21.84	16.88	10.93	23.51	4.04	15.95
1272445	16.00	13.57	10.68	16.32	13.49	10.65	9.20	9.94	16.10	14.67	10.93	8.01	16.03	2.98	11.55
1278800	36.39	29.98	23.72	36.09	30.75	24.28	20.94	22.34	37.38	34.75	23.51	16.03	35.71	6.06	23.56
1371530	6.05	5.08	3.93	6.09	5.14	3.91	3.42	3.65	6.39	5.57	4.04	2.98	6.06	1.28	4.49
1371555	23.92	19.96	15.68	23.72	19.90	15.63	13.62	14.81	24.66	22.12	15.95	11.55	23.56	4.49	17.78

(b) The Upper Basin of the Colorado River

CSU ID	1762500	1800900	1801800	1801816	1802730	1804500	1805400	1810000	1850000	1866000	1880000	1920000	1930000	1960000
1762500	5.77	4.80	16.72	10.23	5.88	6.72	8.57	3.78	4.48	9.66	8.22	11.72	9.11	7.66
1800900	4.80	4.50	14.17	8.53	4.46	5.41	8.19	3.30	3.89	9.41	7.44	10.68	7.98	6.95
1801800	16.72	14.17	63.77	34.20	23.68	19.52	27.44	11.46	13.49	30.11	25.04	37.86	30.37	23.21
1801816	10.23	8.53	34.20	25.32	16.47	14.22	19.65	5.43	8.11	18.55	14.61	20.57	17.56	14.03
1802730	5.88	4.46	23.68	16.47	15.26	9.21	10.82	2.40	4.82	10.90	7.51	11.03	10.90	7.39
1804500	6.72	5.41	19.52	14.22	9.21	11.32	12.72	4.58	4.86	11.14	8.91	12.32	9.82	8.36
1805400	8.57	8.19	27.43	19.65	10.82	12.72	22.40	6.02	6.19	17.92	13.07	18.70	14.19	12.10
1810000	3.78	3.30	11.46	5.43	2.40	4.58	6.02	5.24	2.80	5.82	5.86	9.05	5.90	5.41
1850000	4.48	3.89	13.49	8.11	4.82	4.86	6.19	2.80	2.80	---	---	---	---	---
1866000	9.66	9.41	30.11	18.55	10.90	11.14	17.92	5.82	---	21.68	---	---	---	---
1880000	8.22	7.44	25.04	14.61	7.51	8.91	13.07	5.86	---	---	12.89	---	---	---
1920000	11.72	10.68	37.86	20.57	11.03	12.32	18.70	9.05	---	---	---	27.62	---	---
1930000	9.11	7.98	30.39	17.56	10.90	9.82	14.19	5.90	---	---	---	---	16.33	---
1960000	7.66	6.95	23.21	14.03	7.39	8.36	12.10	5.41	---	---	---	---	---	11.42

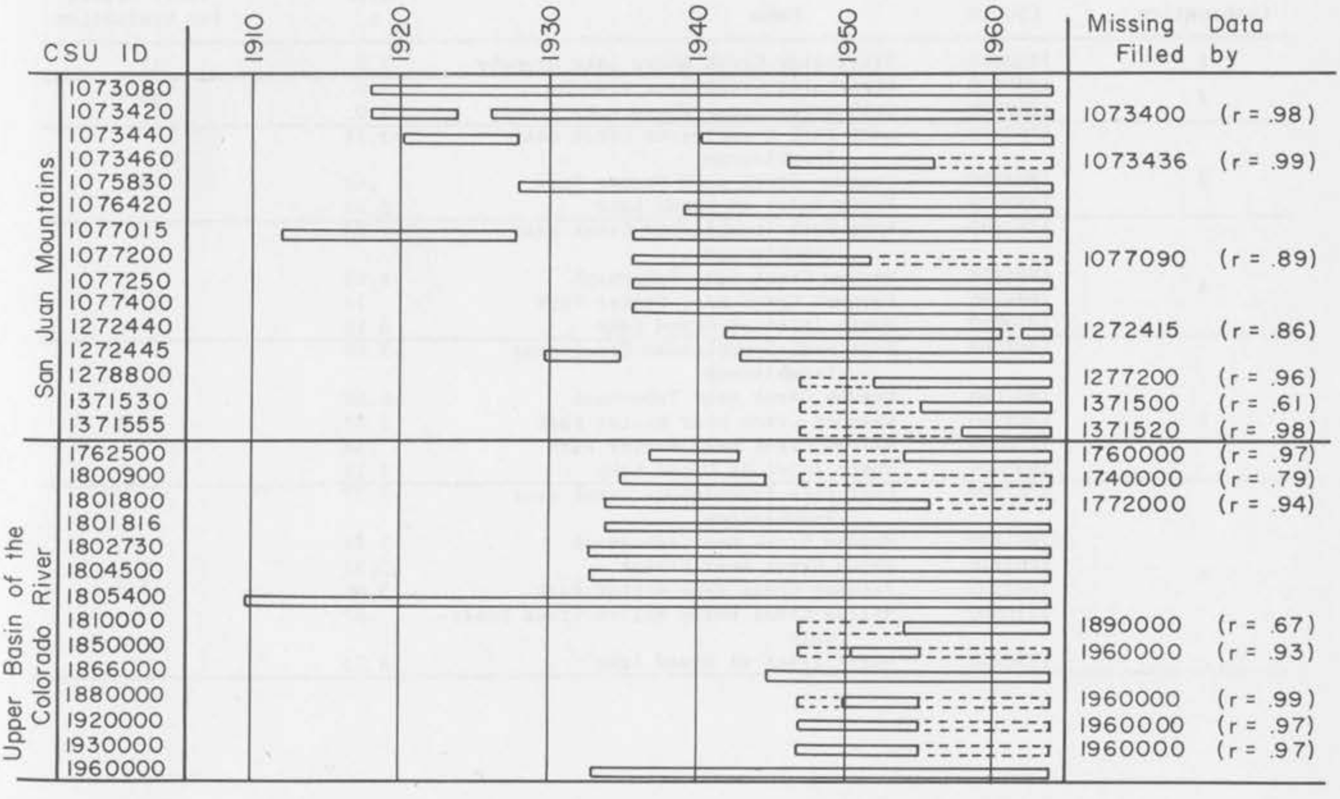

Fig. 11 Length of runoff records in the pilot area

TABLE 4(a) OPTIMAL COMBINATIONS OF GAGES FOR VARIOUS GROUP SIZES IN THE SAN JUAN MOUNTAINS

Number of Sub-basins in Combination	CSU ID	Name	Weight Factor α	Number of Years Needed for Evaluation
1	1371555	Uncompahgre River near Ridgway	1.00	12
2	1272440	Beaver Creek near Norwood	1.00	53
	1371555	Uncompahgre River near Ridgway	1.00	
3	1073080	La Plata River at Hesperus	-9.41	23
	1077015	Navajo River at Edith	4.68	
	1272440	Beaver Creek near Norwood	-2.78	
4	1073080	La Plata River at Hesperus	-9.90	16
	1077015	Navajo River at Edith	8.18	
	1077250	Rio Blanco near Pagosa Springs	-4.27	
	1272440	Beaver Creek near Norwood	-6.38	
5	1073080	La Plata River at Hesperus	-15.13	11
	1077015	Navajo River at Edith	10.80	
	1077250	Rio Blanco near Pagosa Springs	- 6.61	
	1272440	Beaver Creek near Norwood	-11.67	
	1371555	Uncompahgre River near Ridgway	2.09	
6	1076420	Piedra River near Piedra	-7.49	6.1
	1077015	Navajo River at Edith	24.55	
	1077250	Rio Blanco near Pagosa Springs	-32.45	
	1077400	San Juan River at Pagosa Springs	5.31	
	1272440	Beaver Creek near Norwood	-23.36	
	1371530	Dallas Creek near Ridgway	27.38	

TABLE 4(b) OPTIMAL COMBINATIONS OF GAGES FOR VARIOUS GROUP SIZES IN THE UPPER BASIN OF THE COLORADO RIVER

Number of Sub-basins in Combination	CSU ID	Name	Weight Factor α	Number of Years Needed for Evaluation
1	1850000	Stillwater Creek above Lake Grandby	1.0	17
2	1800900	Strawberry Creek near Grandby	1.0	32
	1850000	Stillwater Creek above Lake Granby	1.0	
3	1762500	East Fork Troublesome Creek near Troublesome	-2.38	8.2
	1804500	Vasquez Creek near Winter Park	.59	
	1930000	North Inlet at Grand Lake	2.39	
4	1762500	East Fork Troublesome Creek near Troublesome	-1.83	6.0
	1801800	Meadow Creek near Tabernash	-4.00	
	1804500	Vasquez Creek near Winter Park	.14	
	1930000	North Inlet at Grand Lake	3.10	
5	1762500	East Fork Troublesome Creek near Troublesome	-3.60	3.8
	1801800	Meadow Creek near Tabernash	-6.99	
	1804500	Vasquez Creek near Winter Park	2.67	
	1810000	Willow Creek near Winter Park	.34	
	1930000	North Inlet at Grand Lake	4.15	
6	1762500	East Fork Troublesome Creek near Troublesome	-3.37	2.9
	1801800	Meadow Creek near Tabernash	-5.45	
	1801816	Ranch Creek near Frazer	-2.31	
	1804500	Vasquez Creek near Winter Park	3.60	
	1810000	Willow Creek below Willow Creek Reservoir	.07	
	1930000	North Inlet at Grand Lake	4.51	

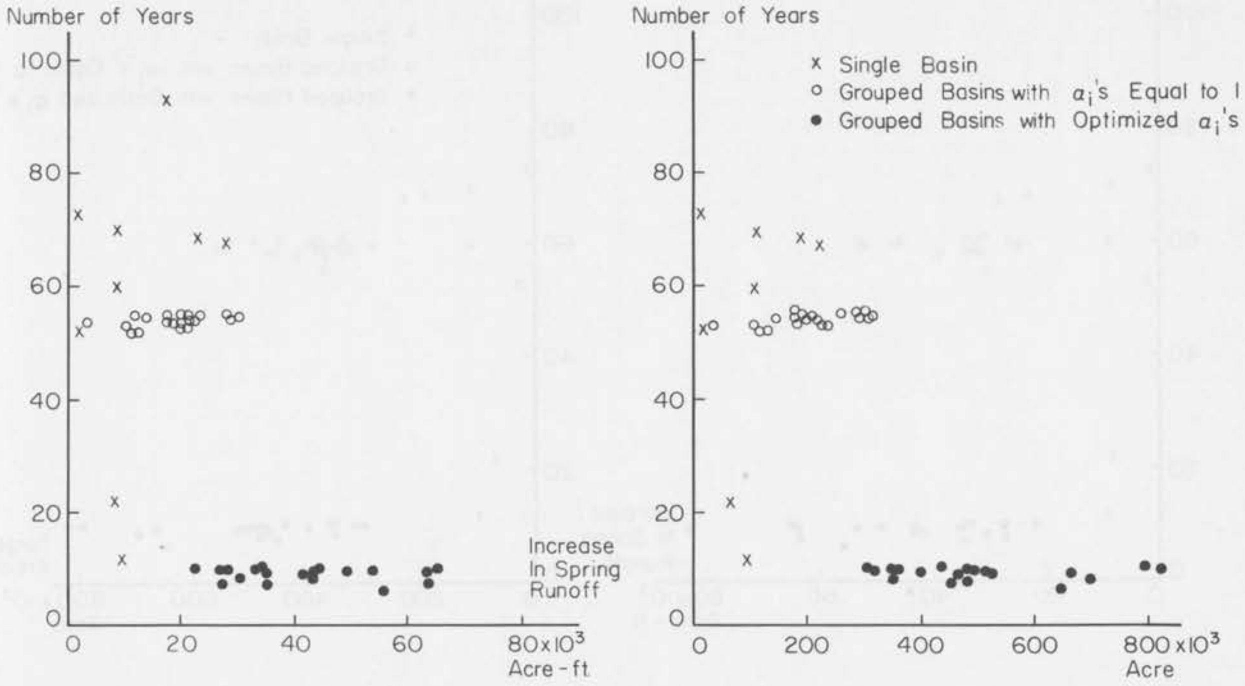

Fig. 12(a) Minimum number of years needed for evaluation for combinations of two through six sub-basins out of 15 in the San Juan Mountains

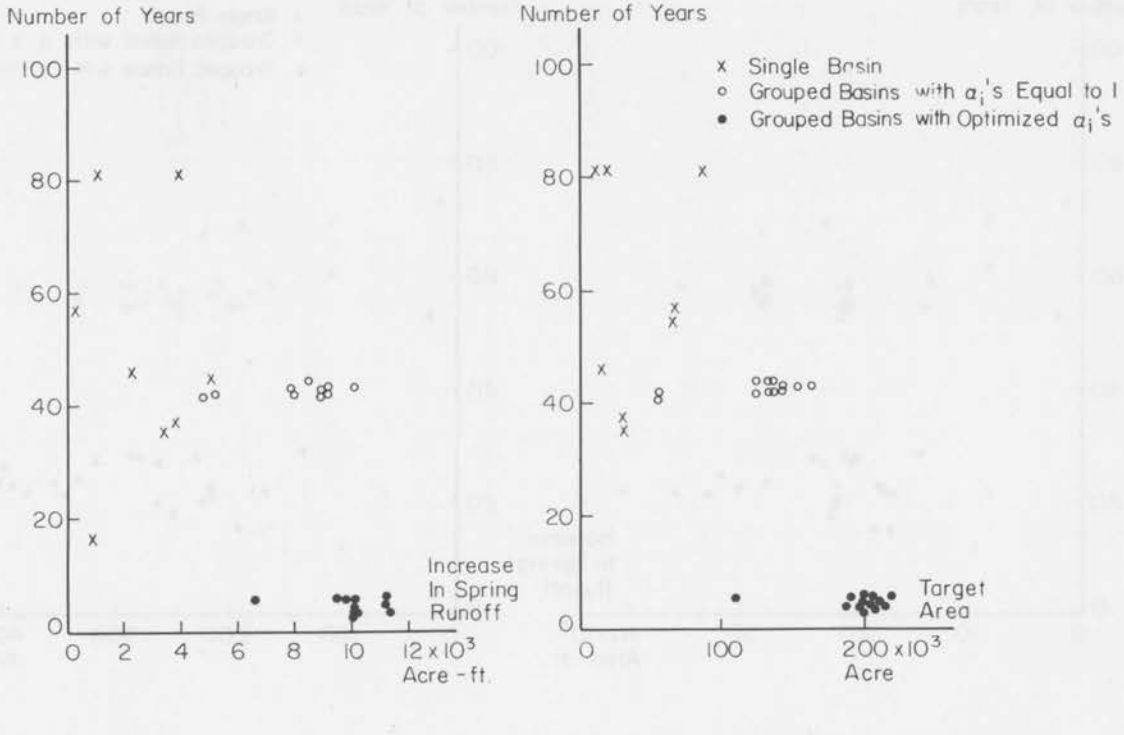

Fig. 12(b) Minimum number of years needed for evaluation for combinations of two through six sub-basins out of 14 in the Upper Basin of the Colorado River

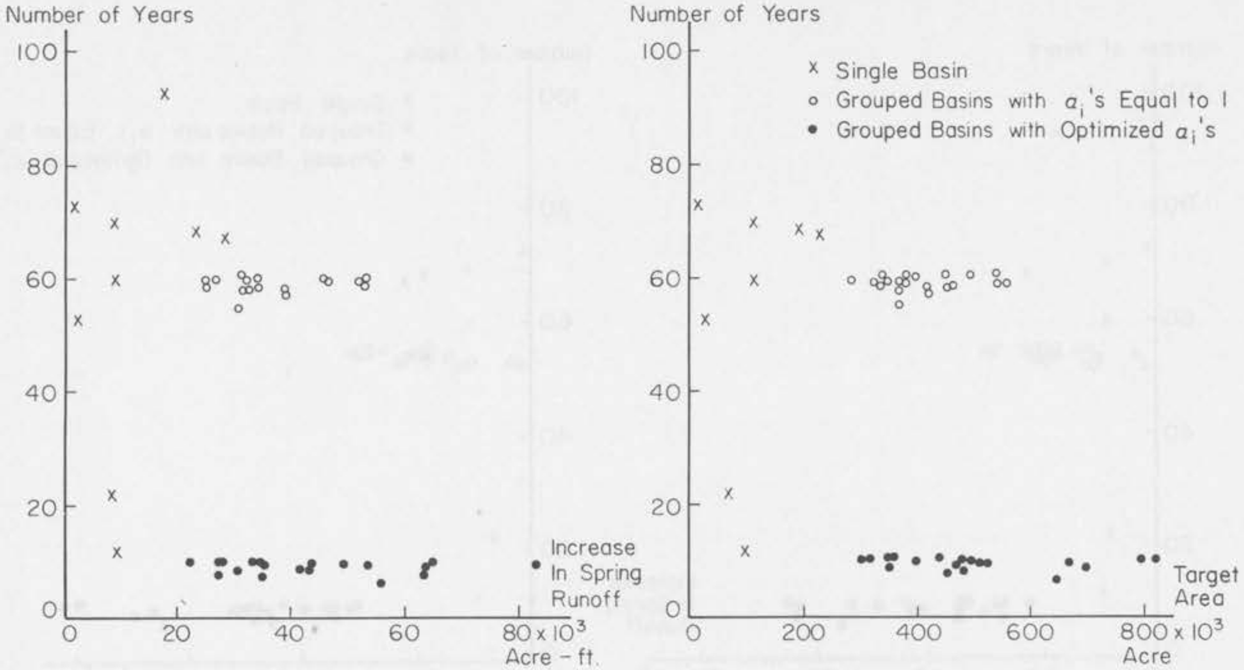

Fig. 12(c) Minimum number of years needed for evaluation for combinations of six sub-basins out of 15 in the San Juan Mountains

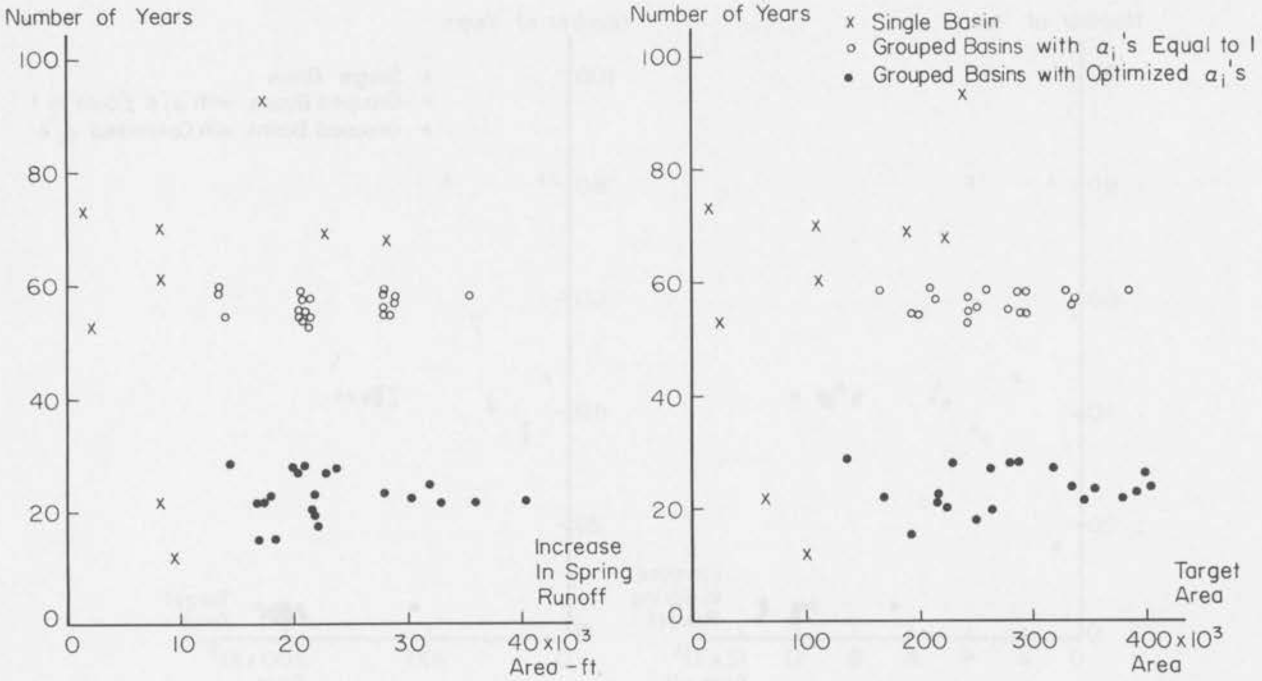

Fig. 12(d) Minimum number of years needed for evaluation for combinations of four sub-basins out of 15 in the San Juan Mountains

TABLE 5(a) 10 BEST COMBINATIONS OF SIX SUB-BASINS IN THE SAN JUAN MOUNTAINS

Rank	Number of Years for Evaluation	α_i	CSU ID	Station Name	Elevation (feet)	Length of Records (years)
1	6.1	- 7.49	1076420	Piedra River near Piedra	6530	26
		24.55	1077015	Navajo River at Edith	7033	45
		-32.45	1077250	Rio Blanco near Pagosa Springs	7950	29
		5.31	1077400	San Juan River at Pagosa Springs	7052	29
		-23.36	1272440	Beaver Creek near Norwood	8008	22
		27.38	1371530	Dallas Creek near Ridgway	6980	14
2	7.7	-14.54	1073080	La Plata River at Hesperus	8105	48
		14.38	1077015	Navajo River at Edith	7033	45
		- 9.90	1077250	Rio Blanco near Pagosa Springs	7950	29
		-14.46	1272440	Beaver Creek near Norwood	8008	22
		- 1.71	1272445	San Miguel Creek near Placerville	7096	28
		18.90	1371530	Dallas Creek near Ridgway	6980	14
3	7.7	-18.86	1073080	La Plata River at Hesperus	8105	48
		16.25	1077015	Navajo River at Edith	7033	45
		- 9.13	1077250	Rio Blanco near Pagosa Springs	7950	29
		-24.72	1272440	Beaver Creek near Norwood	8008	22
		- 1.31	1272445	San Miguel Creek near Placerville	7096	28
		4.33	1371555	Uncompahgre River near Ridgway	6878	6
4	7.9	- 7.37	1076420	Piedra River near Piedra	6530	26
		27.02	1077015	Navajo River at Edith	7033	45
		-31.10	1077250	Rio Blanco near Pagosa Springs	7950	29
		4.70	1077400	San Juan River at Pagosa Springs	7052	29
		-37.00	1272440	Beaver Creek near Norwood	8008	22
		6.06	1371555	Uncompahgre River near Ridgway	6878	6
5	8.4	-14.10	1073080	La Plata River at Hesperus	8105	48
		- 2.32	1073420	Florida River near Durango	7302	42
		14.00	1077015	Navajo River at Edith	7033	45
		- 8.93	1077250	Rio Blanco near Pagosa Springs	7950	29
		-18.16	1272440	Beaver Creek near Norwood	8008	22
		3.21	1371555	Uncompahgre River near Ridgway	6878	6
6	9.0	-20.93	1073080	La Plata River at Hesperus	8105	48
		- .88	1076420	Piedra River near Piedra	6530	26
		19.45	1077015	Navajo River at Edith	7033	45
		-12.54	1077250	Rio Blanco near Pagosa Springs	7950	29
		-21.47	1272440	Beaver Creek near Norwood	8008	22
		3.84	1371555	Uncompahgre River near Ridgway	6878	6
7	9.0	-22.05	1073080	La Plata River at Hesperus	8105	48
		- .59	1075830	Los Pinos River near Bayfield	7515	37
		18.85	1077015	Navajo River at Edith	7033	45
		-10.73	1077250	Rio Blanco near Pagosa Springs	7950	29
		-25.03	1272440	Beaver Creek near Norwood	8008	22
		3.80	1371555	Uncompahgre River near Ridgway	6878	6
8	9.1	- 8.36	1076420	Piedra River near Piedra	6530	26
		24.17	1077015	Navajo River at Edith	7033	45
		-30.86	1077250	Rio Blanco near Pagosa Springs	7950	29
		3.54	1077400	San Juan River at Pagosa Springs	7052	29
		-42.16	1272440	Beaver Creek near Norwood	8008	22
		15.30	1278800	Dolores River below Rico	8422	13
9	9.3	-29.89	1073080	La Plata River at Hesperus	8105	48
		- .70	1073460	Animas River above Tacoma	7520	11
		25.30	1077015	Navajo River at Edith	7033	45
		-14.72	1077250	Rio Blanco near Pagosa Springs	7950	29
		-30.20	1272440	Beaver Creek near Norwood	8008	22
		5.11	1371555	Uncompahgre River near Ridgway	6878	6
10	9.4	-16.80	1073080	La Plata River at Hesperus	8105	48
		1.95	1073448	Hermosa Creek near Hermosa	6706	36
		15.71	1077015	Navajo River at Edith	7033	45
		-10.69	1077250	Rio Blanco near Pagosa Springs	7950	29
		-14.95	1272440	Beaver Creek near Norwood	8008	22
		3.32	1371555	Uncompahgre River near Ridgway	6878	6

TABLE 5(b) 10 BEST COMBINATIONS OF FIVE SUB-BASINS IN THE SAN JUAN MOUNTAINS

Rank	Number of Years for Evaluation	α_i	CSU ID	Station Name	Elevation (feet)	Length of Records (years)
1	11	-15.13	1073080	La Plata River at Hesperus	8105	48
		10.80	1077015	Navajo River at Edith	7033	45
		- 6.61	1077250	Rio Blanco near Pagosa Springs	7950	29
		-11.67	1272440	Beaver Creek near Norwood	8008	22
		2.09	1371555	Uncompahgre River near Ridgway	6878	6
2	12	-10.93	1073080	La Plata River at Hesperus	8105	48
		8.36	1077015	Navajo River at Edith	7033	45
		- 5.41	1077250	Rio Blanco near Pagosa Springs	7950	29
		- 6.39	1272440	Beaver Creek near Norwood	8008	22
		5.36	1371530	Dallas Creek near Ridgway	6980	14
3	14	-15.75	1073080	La Plate River at Hesperus	8105	48
		10.42	1077015	Navajo River at Edith	7033	45
		- 6.26	1077250	Rio Blanco near Pagosa Springs	7950	29
		-11.30	1272440	Beaver Creek near Norwood	8008	22
		2.42	1278800	Dolores River below Rico	8422	13
4	14	- 4.05	1076420	Piedra River near Piedra	6530	26
		15.22	1077015	Navajo River at Edith	7033	45
		-18.47	1077250	Rio Blanco near Pagosa Springs	7950	29
		-26.12	1272440	Beaver Creek near Norwood	8008	22
		12.62	1278800	Dolores River below Rico	8422	13
5	15	-24.66	1073080	La Plata River at Hesperus	8105	48
		.65	1077400	San Juan River at Pagosa Springs	7052	29
		17.77	1077015	Navajo River at Edith	7033	45
		- 9.91	1077250	Rio Blanco near Pagosa Springs	7950	29
		-14.96	1272440	Beaver Creek near Norwood	8008	22
6	15	-10.73	1073080	La Plata River at Hesperus	8105	48
		8.07	1077015	Navajo River at Edith	7033	45
		5.34	1077200	Rito Blanco near Pagosa Springs	7330	17
		- 4.51	1077250	Rio Blanco near Pagosa Springs	7950	29
		- 7.20	1272440	Beaver Creek near Norwood	8008	22
7	15	- 5.21	1073420	Florida River near Durango	7302	42
		12.53	1077015	Navajo River at Edith	7033	45
		-11.73	1077250	Rio Blanco near Pagosa Springs	7950	29
		-18.43	1272440	Beaver Creek near Norwood	8008	22
		3.75	1371555	Uncompahgre River near Ridgway	6878	6
8	15	-15.90	1073080	La Plata River at Hesperus	8105	48
		.50	1073448	Hermosa Creek near Hermosa	6706	36
		11.84	1077015	Navajo River at Edith	7033	45
		- 6.03	1077250	Rio Blanco near Pagosa Springs	7950	29
		- 9.35	1272440	Beaver Creek near Norwood	8008	22
9	15	-18.36	1073080	La Plata River at Hesperus	8105	48
		- .33	1076420	Piedra River near Piedra	6530	26
		17.13	1077015	Navajo River at Edith	7033	45
		- 9.21	1077250	Rio Blanco near Pagosa Springs	7950	29
		-13.26	1272440	Beaver Creek near Norwood	8008	22
10	16	- 6.00	1076420	Piedra River near Piedra	6530	26
		25.83	1077015	Navajo River at Edith	7033	45
		-26.41	1077250	Rio Blanco near Pagosa Springs	7950	29
		4.11	1077400	San Juan River at Pagosa Springs	7052	29
		-23.92	1272440	Beaver Creek near Norwood	8008	22

TABLE 5(c) 10 BEST COMBINATIONS OF FOUR SUB-BASINS IN THE SAN JUAN MOUNTAINS

Rank	Number of Years for Evaluation	α_i	CSU ID	Station Name	Elevation (feet)	Length of Records (years)
1	16	- 9.90	1073080	La Plata River at Hesperus	8105	48
		8.18	1077015	Navajo River at Edith	7033	45
		- 4.27	1077250	Rio Blanco near Pagosa Springs	7950	29
		- 6.38	1272440	Beaver Creek near Norwood	8008	22
2	18	-16.03	1073080	La Plata River at Hesperus	8105	48
		6.57	1077015	Navajo River at Edith	7033	45
		- 6.34	1272440	Beaver Creek near Norwood	8008	22
		1.68	1371555	Uncompahgre River near Ridgway	6878	6
3	20	-18.25	1073080	La Plata River at Hesperus	8105	48
		1.93	1073448	Hermosa Creek near Hermosa	6706	36
		6.99	1077015	Navajo River at Edith	7033	45
		- 6.64	1272440	Beaver Creek near Norwood	8008	22
4	21	-16.41	1073080	La Plata River at Hesperus	8105	48
		6.22	1077015	Navajo River at Edith	7033	45
		- 6.60	1272440	Beaver Creek near Norwood	8008	22
		2.22	1278800	Dolores River below Rico	8422	13
5	22	-27.61	1073080	La Plata River at Hesperus	8105	48
		11.91	1077015	Navajo River at Edith	7033	45
		.66	1077400	San Juan River at Pagosa Springs	7052	29
		- 8.94	1272440	Beaver Creek near Norwood	8008	22
6	22	-10.69	1073080	La Plata River at Hesperus	8105	48
		4.87	1077015	Navajo River at Edith	7033	45
		- 2.92	1272440	Beaver Creek near Norwood	8008	22
		2.26	1371530	Dallas Creek near Ridgway	6980	14
7	22	-10.39	1073080	La Plata River at Hesperus	8105	48
		4.38	1077015	Navajo River at Edith	7033	45
		6.10	1077200	Rito Blanco near Pagosa Springs	7330	17
		- 3.55	1272440	Beaver Creek near Norwood	8008	22
8	22	-31.32	1073080	La Plata River at Hesperus	8105	48
		.68	1073460	Animas River above Tacoma	7520	11
		13.57	1077015	Navajo River at Edith	7033	45
		-11.23	1272440	Beaver Creek near Norwood	8008	22
9	23	-23.64	1073080	La Plata River at Hesperus	8105	48
		.34	1076420	Piedra River near Piedra	6530	26
		11.10	1077015	Navajo River at Edith	7033	45
		- 8.22	1272440	Beaver Creek near Norwood	8008	22
10	23	14.41	1073080	La Plata River at Hesperus	8105	48
		.67	1073420	Florida River near Durango	7302	42
		6.73	1077015	Navajo River at Edith	7033	45
		- 4.93	1272440	Beaver Creek near Norwood	8008	22

TABLE 5(d) 10 BEST COMBINATIONS OF THREE SUB-BASINS IN THE SAN JUAN MOUNTAINS

Rank	Number of Years for Evaluation	α_i	CSU ID	Station Name	Elevation (feet)	Length of Records (years)
1	23	- 9.41	1073080	La Plata River at Hesperus	8105	48
		4.68	1077015	Navajo River at Edith	7033	45
		- 2.78	1272440	Beaver Creek near Norwood	8008	22
2	34	-16.81	1073420	Florida River near Durango	7302	42
		5.17	1073460	Animas River above Tacoma	7520	11
		-10.74	1272440	Beaver Creek near Norwood	8008	22
3	34	- 9.42	1073080	La Plata River at Hesperus	8105	48
		7.41	1077015	Navajo River at Edith	7033	45
		- 2.60	1278800	Dolores River below Rico	8422	13
4	34	5.53	1077015	Navajo River at Edith	7033	45
		- 6.18	1077250	Rio Blanco near Pagosa Springs	7950	29
		- 3.67	1272440	Beaver Creek near Norwood	8008	22
5	35	- 2.72	1073080	La Plata River at Hesperus	8105	48
		11.38	1077200	Rito Blanco near Pagosa Spring	7330	17
		- 1.21	1272440	Beaver Creek near Norwood	8008	22
6	37	- 8.35	1073080	La Plata River at Hesperus	8105	48
		5.59	1077015	Navajo River at Edith	7033	45
		- .98	1371555	Uncompahgre River near Ridgway	6787	6
7	38	6.28	1073460	Animas River above Tacoma	7520	11
		- 6.39	1075830	Los Pinos River near Bayfield	7515	37
		-14.81	1272440	Beaver Creek near Norwood	8008	22
8	39	- 6.18	1073080	La Plata River at Hesperus	8105	48
		- 5.11	1272440	Beaver Creek near Norwood	8008	22
		4.34	1278800	Dolores River below Rico	8422	13
9	39	6.16	1073460	Animas River above Tacoma	7520	11
		-10.55	1076420	Piedra River near Piedra	6530	26
		3.47	1077400	San Juan River at Pagosa Spring	7052	29
10	41	-12.38	1073080	La Plata River at Hesperus	8105	48
		5.55	1073460	Animas River above Tacoma	7520	11
		- 4.54	1076420	Piedra River near Piedra	6530	26

TABLE 5(e) 10 BEST COMBINATIONS OF TWO SUB-BASINS IN THE SAN JUAN MOUNTAINS

Rank	Number of Years for Evaluation	α_i	CSU ID	Station Name	Elevation (feet)	Length of Records (years)
1	53	1.00	1272440	Beaver Creek near Norwood	8008	22
		1.00	1371555	Uncompahgre River near Ridgway	6878	6
2	54	1.00	1077200	Rito Blanco near Pagosa Springs	7330	17
		1.00	1272440	Beaver Creek near Norwood	8008	22
3	54	1.00	1077200	Rito Blanco near Pagosa Springs	7330	17
		1.00	1371555	Uncompahgre River near Ridgway	6878	6
4	54	1.00	1077015	Navajo River at Edith	7033	45
		1.00	1371555	Uncompahgre River near Ridgway	6878	6
5	55	1.00	1278800	Dolores River below Rico	8422	13
		1.00	1371555	Uncompahgre River near Ridgway	6878	6
6	57	1.00	1371530	Dallas Creek near Ridgway	6980	14
		1.00	1371555	Uncompahgre River near Ridgway	6878	6
7	58	1.00	1272440	Beaver Creek near Norwood	8008	22
		1.00	1278800	Dolores River below Rico	8422	13
8	58	1.00	1077015	Navajo River at Edith	7033	45
		1.00	1272440	Beaver Creek near Norwood	8008	22
9	59	1.00	1077200	Rito Blanco near Pagosa Springs	7330	17
		1.00	1278800	Dolores River below Rico	8422	13
10	59	1.00	1077015	Navajo River at Edith	7033	45
		1.00	1278800	Dolores River below Rico	8422	13

TABLE 6(a) 10 BEST COMBINATIONS OF SIX SUB-BASINS IN THE UPPER BASIN OF THE COLORADO RIVER

Rank	Number of Years for Evaluation	α_i	CSU ID	Station Name	Elevation (feet)	Length of Records (years)
1	2.9	- 3.37	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		- 5.45	1801800	Meadow Creek near Tabernash	9780	21
		- 2.31	1801816	Ranch Creek near Fraser	8670	30
		3.60	1804500	Vasquez Creek near Winter Park	8769	31
		.07	1810000	Willow Creek below Willow Creek Reservoir	8024	11
		4.51	1930000	North Inlet at Grand Lake	8380	14
2	3.5	- 4.04	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		- 6.79	1801800	Meadow Creek near Tabernash	9780	21
		- .49	1802730	St. Louis Creek near Fraser	8980	31
		2.96	1804500	Vasquez Creek near Winter Park	8769	31
		.18	1810000	Willow Creek below Willow Creek Reservoir	8024	11
		4.89	1930000	North Inlet at Grand Lake	8380	14
3	3.6	- 3.41	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		- 3.72	1800900	Strawberry Creek near Granby	8650	10
		- 7.67	1801800	Meadow Creek near Tabernash	9780	21
		2.77	1804500	Vasquez Creek near Winter Park	8769	31
		.38	1810000	Willow Creek below Willow Creek Reservoir	8024	11
		4.59	1930000	North Inlet at Grand Lake	8380	14
4	3.8	- 3.38	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		- 6.93	1801800	Meadow Creek near Tabernash	9780	21
		1.89	1804500	Vasquez Creek near Winter Park	8769	31
		- .19	1805400	Fraser River near Winter Park	8900	54
		.05	1810000	Willow Creek below Willow Creek Reservoir	8024	11
		4.78	1930000	North Inlet at Grand Lake	8380	14
5	3.9	- 4.23	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		- 3.19	1801816	Ranch Creek near Fraser	8670	30
		- .70	1802730	St. Louis Creek near Fraser	8980	31
		4.58	1804500	Vasquez Creek near Winter Park	8769	31
		- .16	1810000	Willow Creek below Willow Creek Reservoir	8024	11
		4.54	1930000	North Inlet at Grand Lake	8380	14
6	4.2	- 3.83	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		.13	1800900	Strawberry Creek near Granby	8650	10
		- 3.65	1801816	Ranch Creek near Fraser	8670	30
		4.37	1804500	Vasquez Creek near Winter Park	8769	31
		.01	1810000	Willow Creek below Willow Creek Reservoir	8024	11
		3.88	1930000	North Inlet at Grand Lake	8380	14
7	4.4	- 3.61	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		- 3.63	1801816	Ranch Creek near Fraser	8670	30
		3.62	1804500	Vasquez Creek near Winter Park	8769	31
		.01	1805400	Fraser River near Winter Park	8900	54
		- .22	1810000	Willow Creek below Willow Creek Reservoir	8024	11
		4.33	1930000	North Inlet at Grand Lake	8380	14
8	4.8	- 4.79	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		- 5.71	1800900	Strawberry Creek near Granby	8650	10
		- 1.98	1802730	St. Louis Creek near Fraser	8980	31
		4.40	1804500	Vasquez Creek near Winter Park	8769	31
		.02	1810000	Willow Creek below Willow Creek Reservoir	8024	11
		4.86	1930000	North Inlet at Grand Lake	8380	14

TABLE 6(a) continued

9	5.1	-2.72	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		-9.58	1801800	Meadow Creek near Tabernash	9780	21
		-1.00	1801816	Ranch Creek near Fraser	8670	30
		1.29	1802730	St. Louis Creek near Fraser	8980	31
		.62	1810000	Willow Creek below Willow Creek Reservoir	8024	11
		4.76	1930000	North Inlet at Grand Lake	8380	14
10	5.4	-2.96	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		-8.75	1801800	Meadow Creek near Tabernash	9780	21
		.64	1802730	St. Louis Creek near Fraser	8980	31
		.04	1805400	Fraser River near Winter Park	8900	54
		.29	1810000	Willow Creek below Willow Creek Res.	8024	11
		5.03	1930000	North Inlet at Grand Lake	8380	14

TABLE 6(b) 10 BEST COMBINATIONS OF FIVE SUB-BASINS IN THE UPPER BASIN OF THE COLORADO RIVER

Rank	Number of Years for Evaluation	α_1	CSU ID	Station Name	Elevation (feet)	Length of Records (years)
1	3.8	-3.60	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		-6.99	1801800	Meadow Creek near Tabernash	9780	21
		2.67	1804500	Vasquez Creek near Winter Park	8769	31
		.34	1810000	Willow Creek near Winter Park	8024	11
		4.15	1930000	North Inlet at Grand Lake	8380	14
2	4.2	-3.71	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		-3.54	1801816	Ranch Creek near Fraser	8670	30
		4.28	1804500	Vasquez Creek near Winter Park	8769	31
		.02	1810000	Willow Creek near Winter Park	8024	11
		3.74	1930000	North Inlet at Grand Lake	8380	14
3	5.0	-4.98	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		-1.63	1802730	St. Louis Creek near Fraser	8980	31
		4.00	1804500	Vasquez Creek near Winter Park	8769	31
		.03	1810000	Willow Creek near Winter Park	8024	11
		4.26	1930000	North Inlet at Grand Lake	8380	14
4	5.3	-1.53	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		-5.73	1800900	Strawberry Creek near Granby	8650	10
		-5.02	1801800	Meadow Creek near Tabernash	9780	21
		.52	1804500	Vasquez Creek near Winter Park	8769	31
		3.71	1930000	North Inlet at Grand Lake	8380	14
5	5.4	-2.85	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		-9.25	1801800	Meadow Creek near Tabernash	9780	21
		.92	1802730	St. Louis Creek near Fraser	8980	31
		.67	1810000	Willow Creek below Willow Creek Reservoir	8024	11
		4.41	1930000	North Inlet at Grand Lake	8380	14
6	5.5	-2.85	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		-9.25	1801800	Meadow Creek near Tabernash	9780	21
		.92	1802730	St. Louis Creek near Fraser	8980	31
		.67	1810000	Willow Creek below Willow Creek Reservoir	8024	11
		4.42	1930000	North Inlet at Grand Lake	8380	14
7	6.1	-2.63	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		-6.66	1801800	Meadow Creek near Tabernash	9780	21
		-.16	1805400	Fraser River near Winter Park	8900	54
		.28	1810000	Willow Creek below Willow Creek Reservoir	8024	11
		4.49	1930000	North Inlet at Grand Lake	8380	14

TABLE 6(b) continued

8	6.3	- 3.01	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		- 7.83	1801800	Meadow Creek near Tabernash	9780	21
		.61	1801816	Ranch Creek near Fraser	8670	30
		.69	1810000	Willow Creek below Willow Creek Reservoir	8024	11
		4.29	1930000	North Inlet at Grand Lake	8380	14
9	6.7	- 1.93	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		- 4.11	1801800	Meadow Creek near Tabernash	9780	21
		- .26	1801816	Ranch Creek near Fraser	8670	30
		- .07	1804500	Vasquez Creek near Winter Park	8769	31
		3.48	1930000	North Inlet at Grand Lake	8380	14
10	6.7	- 4.95	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		3.75	1800900	Strawberry Creek near Granby	8650	10
		2.91	1804500	Vasques Creek near Winter Park	8769	31
		.39	1810000	Willow Creek below Willow Creek Reservoir	8024	11
		3.01	1930000	North Inlet at Grand Lake	8380	14

TABLE 6(c) 10 BEST COMBINATIONS OF FOUR SUB-BASINS IN THE UPPER BASIN OF THE COLORADO RIVER

Rank	Number of Years for Evaluation	α_i	CSU ID	Station Name	Elevation (feet)	Length of Records (years)
1	6.0	- 1.83	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		- 4.00	1801800	Meadow Creek near Tabernash	9780	21
		.14	1804500	Vasquez Creek near Winter Park	8769	31
		3.10	1930000	North Inlet at Grand Lake	8380	14
2	6.9	- 2.66	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		- 6.95	1801800	Meadow Creek near Tabernash	9780	21
		.73	1810000	Willow Creek below Willow Creek Reservoir	8024	11
		3.90	1930000	North Inlet at Grand Lake	8380	14
3	6.9	- 4.59	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		2.94	1804500	Vasquez Creek near Winter Park	8769	31
		.44	1810000	Willow Creek below Willow Creek Reservoir	8024	11
		3.10	1930000	North Inlet at Grand Lake	8380	14
4	7.3	- 2.21	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		9.28	1800900	Strawberry Creek near Granby	8650	10
		- .15	1810000	Willow Creek below Willow Creek Reservoir	8024	11
		7.71	1850000	Stillwater Creek above Lake Granby	8310	5
5	7.9	- 2.17	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		- 1.04	1801816	Ranch Creek near Fraser	8670	30
		.30	1804500	Vasquez Creek near Winter Park	8769	31
		2.82	1930000	North Inlet at Grand Lake	8380	14
6	8.2	- 2.50	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		- .56	1800900	Strawberry Creek near Granby	8650	10
		.68	1804500	Vasquez Creek near Winter Park	8769	31
		2.57	1930000	North Inlet at Grand Lake	8380	14
7	8.4	- 3.26	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		- .52	1805400	Fraser River near Winter Park	8900	54
		.30	1810000	Willow Creek below Willow Creek Reservoir	8024	11
		3.58	1930000	North Inlet at Grand Lake	8380	14
8	8.5	-10.78	1800900	Strawberry Creek near Granby	8650	10
		- 7.23	1801800	Meadow Creek near Tabernash	9780	21
		.94	1804500	Vasquez Creek near Winter Park	8769	31
		3.48	1930000	North Inlet at Grand Lake	8380	14

TABLE 6(c) continued

9	8.7	- .78	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		-10.25	1800900	Strawberry Creek near Granby	8650	10
		- 4.15	1801800	Meadow Creek near Tabernash	9780	21
		3.59	1930000	North Inlet at Grand Lake	8380	14
10	9.1	- 1.11	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		- .45	1804500	Vasquez Creek near Winter Park	8769	31
		- .29	1810000	Willow Creek below Willow Creek Reservoir	8024	11
		11.95	1850000	Stillwater Creek above Lake Granby	8310	5

TABLE 6(d) 10 BEST COMBINATIONS OF THREE SUB-BASINS IN THE UPPER BASIN OF THE COLORADO RIVER

Rank	Number of Years for Evaluation	α_i	CSU ID	Station Name	Elevation (feet)	Length of (years)
1	8.2	- 2.38	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		.59	1804500	Vasquez Creek near Winter Park	8769	31
		2.39	1930000	North Inlet at Grand Lake	8380	14
2	9.5	- .94	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		- .30	1810000	Willow Creek below Willow Creek Reservoir	8024	11
		9.87	1850000	Stillwater Creek above Lake Granby	8310	5
3	9.8	- 8.57	1800900	Strawberry Creek near Granby	8650	10
		- 5.18	1801800	Meadow Creek near Tabernash	9780	21
		2.92	1930000	North Inlet at Grand Lake	8380	14
4	11	- 7.76	1800900	Strawberry Creek near Granby	8650	10
		- .07	1810000	Willow Creek below Willow Creek Reservoir	8024	11
		9.44	1850000	Stillwater Creek above Lake Granby	8310	5
5	12	- 1.67	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		- 3.91	1800900	Strawberry Creek near Granby	8650	10
		2.49	1930000	North Inlet at Grand Lake	8380	14
6	12	- 3.61	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		.88	1810000	Willow Creek below Willow Creek Reservoir	8024	11
		2.85	1930000	North Inlet at Grand Lake	8380	14
7	12	- 1.79	1801816	Ranch Creek near Fraser	8670	30
		- .18	1810000	Willow Creek below Willow Creek Reservoir	8024	11
		8.68	1850000	Stillwater Creek above Lake Granby	8310	5
8	13	- 2.58	1801800	Meadow Creek near Tabernash	9780	21
		- .11	1810000	Willow Creek below Willow Creek Reservoir	8024	11
		8.31	1850000	Stillwater Creek above Lake Granby	8310	5
9	14	- 7.23	1801800	Meadow Creek near Tabernash	9780	21
		.15	1804500	Vasquez Creek near Winter Park	8769	31
		2.54	1930000	North Inlet at Grand Lake	8380	14
10	14	- 4.21	1762500	East Fork Troublesome Creek near Troublesome	7750	17
		1.28	1804500	Vasquez Creek near Winter Park	8769	31
		2.23	1960000	Colorado River near Grand Lake	8380	45

TABLE 6(e) 10 BEST COMBINATIONS OF TWO SUB-BASINS IN THE UPPER BASIN OF THE COLORADO RIVER

Rank	Number of Years for Evaluation	α_i	CSU ID	Station Name	Elevation (feet)	Length of Records (years)
1	32	1.00	1800900	Strawberry Creek near Granby	8650	10
		1.00	1850000	Stillwater Creek above Lake Granby	8310	5
2	39	1.00	1800900	Strawberry Creek near Granby	8650	10
		1.00	1930000	North Inlet at Grand Lake	8380	14
3	41	1.00	1804500	Vasquez Creek near Winter Park	8769	31
		1.00	1930000	North Inlet at Grand Lake	8380	14
4	41	1.00	1800900	Strawberry Creek near Granby	8650	10
		1.00	1866000	Arapaho Creek at Monarch Outlet	8310	20
5	42	1.00	1804500	Vasquez Creek near Winter Park	8769	31
		1.00	1866000	Arapaho Creek at Monarch Outlet	8310	20
6	42	1.00	1810000	Willow Creek below Willow Creek Reservoir	8024	11
		1.00	1866000	Arapaho Creek at Monarch Outlet	8310	20
7	44	1.00	1801800	Meadow Creek near Tabernash	9780	21
		1.00	1866000	Arapaho Creek at Monarch Outlet	8310	20
8	45	1.00	1810000	Willow Creek below Willow Creek Reservoir	8024	11
		1.00	1930000	North Inlet at Grand Lake	8380	14
9	45	1.00	1801800	Meadow Creek near Tabernash	9780	21
		1.00	1930000	North Inlet at Grand Lake	8380	14
10	46	1.00	1804500	Vasquez Creek near Winter Park	8769	31
		1.00	1850000	Stillwater Creek above Lake Granby	8310	5

TABLE 7(a) SENSITIVITY OF NUMBER OF YEARS FOR EVALUATION ACCORDING TO CHANGE OF COEFFICIENTS (THE SAN JUAN MOUNTAINS)

Rank	Combination of Sub-basins and Coefficients							Number of Years for Evaluation
1	CSU ID	1076420	1077015	1077250	1077400	1272440	1371530	
	Optimized	- 7.49	24.55	-32.45	5.31	-23.36	27.38	6.08
	1% change	- 7.57	24.80	-32.70	5.33	-23.59	27.40	6.09
	5% change	- 7.86	25.78	-33.69	5.45	-24.50	27.45	6.23
	10% change	- 8.23	27.01	-34.93	5.59	-25.63	27.53	6.56
2	CSU ID	1073080	1077015	1077250	1272440	1272445	1371530	
	Optimized	-14.54	14.38	- 9.90	-14.46	- 1.71	18.90	7.68
	1% change	-14.68	14.53	-10.01	-14.62	- 1.73	18.94	7.68
	5% change	-15.26	15.10	-10.43	-15.27	- 1.81	19.09	7.86
	10% change	-15.99	15.82	-10.97	-16.09	- 1.90	19.29	8.42
3	CSU ID	1073080	1077015	1077250	1272440	1272445	1371555	
	Optimized	-18.86	16.25	- 9.13	-24.72	- 1.32	4.34	7.69
	1% change	-19.05	16.42	- 9.23	-24.85	- 1.33	4.32	7.70
	5% change	-19.80	17.07	- 9.66	-25.36	- 1.36	4.24	7.84
	10% change	-20.75	17.88	-10.20	-26.00	- 1.41	4.14	8.27
4	CSU ID	1076420	1077015	1077250	1077400	1272440	1371555	
	Optimized	- 7.37	27.02	-31.10	4.70	-37.00	6.06	7.88
	1% change	- 7.44	27.29	-31.36	4.72	-37.20	6.04	7.88
	5% change	- 7.73	28.37	-32.39	4.83	-37.97	5.94	8.00
	10% change	- 8.10	29.72	-33.68	4.97	-38.95	5.82	8.36
5	CSU ID	1073080	1073420	1077015	1077250	1272440	1371555	
	Optimized	-14.10	- 2.33	14.00	- 8.93	-18.16	3.21	8.44
	1% change	-14.24	- 2.35	14.03	- 8.89	-18.22	3.21	8.44
	5% change	-14.80	- 2.44	14.18	- 8.71	-18.46	3.24	8.49
	10% change	-15.50	- 2.56	14.37	- 8.50	-18.76	3.28	8.64
6	CSU ID	1073080	1076420	1077015	1077250	1272440	1371555	
	Optimized	-20.93	- .88	19.45	-12.54	-21.47	3.84	9.01
	1% change	-21.14	- .89	19.50	-12.49	-21.52	3.85	9.01
	5% change	-21.98	- .92	19.72	-12.25	-21.71	3.86	9.06
	10% change	-23.03	- .97	19.98	-11.95	-21.96	3.88	9.21
7	CSU ID	1073080	1075830	1077015	1077250	1272440	1371555	
	Optimized	-22.05	- .59	18.85	-10.73	-25.03	3.80	9.05
	1% change	-22.27	- .60	18.90	-10.66	-25.09	3.81	9.05
	5% change	-23.15	- .62	19.08	-10.38	-25.33	3.82	9.10
	10% change	-24.26	- .65	19.31	-10.03	-25.63	3.84	9.25

TABLE 7(a) continued

	CSU ID	1076420	1077015	1077250	1077400	1272440	1278800	
	Optimized	- 8.36	24.17	-30.86	3.54	-42.16	15.30	9.13
8	1% change	- 8.44	24.41	-31.08	3.59	-42.35	15.25	9.14
	5% change	- 8.78	25.38	-31.95	3.77	-43.11	15.06	9.25
	10% change	- 9.19	26.59	-33.04	4.00	-44.05	14.83	9.60
	CSU ID	1073080	1073460	1077015	1077250	1272440	1371555	
	Optimized	-29.89	- .70	25.30	-14.72	-30.20	5.11	9.26
9	1% change	-30.19	- .70	25.38	-14.63	-30.28	5.12	9.26
	5% change	-31.38	- .73	25.67	-14.30	-30.60	5.15	9.31
	10% change	-32.88	- .77	26.04	-13.89	-30.99	5.19	9.46
	CSU ID	1073080	1073448	1077015	1077250	1272440	1371555	
	Optimized	-16.80	- 1.95	15.71	-10.69	-14.95	3.32	9.44
10	1% change	-16.97	- 1.97	15.75	-10.65	-14.98	3.33	9.44
	5% change	-17.64	- 2.04	15.94	-10.49	-15.11	3.36	9.49
	10% change	-18.48	- 2.14	16.17	-10.28	-15.26	3.39	9.63

TABLE 7(b) SENSITIVITY OF NUMBER OF YEARS FOR EVALUATION ACCORDING TO CHANGE OF COEFFICIENTS (THE UPPER BASIN OF THE COLORADO RIVER)

Rank	Combination of Sub-basins and Coefficients							Number of Years for Evaluation
	CSU ID	1762500	1801800	1801816	1804500	1810000	1930000	
	Optimized	- 3.37	- 5.45	- 2.31	3.60	.07	4.51	2.90
1	1% change	- 3.41	- 5.51	- 2.24	3.58	.08	4.52	2.90
	5% change	- 3.54	- 5.72	- 1.98	3.51	.09	4.56	2.93
	10% change	- 3.71	- 6.00	- 1.65	3.43	.11	4.60	3.02
	CSU ID	1762500	1801800	1802730	1804500	1810000	1930000	
	Optimized	- 4.04	- 6.79	- .49	2.96	.18	4.89	3.53
2	1% change	- 4.08	- 6.86	- .47	2.97	.17	4.91	3.54
	5% change	- 4.24	- 7.13	- .41	3.01	.16	5.00	3.62
	10% change	- 4.45	- 7.47	- .34	3.07	.14	5.10	3.87
	CSU ID	1762500	1800900	1801800	1804500	1810000	1930000	
	Optimized	- 3.41	- 3.72	- 7.67	2.77	.38	4.59	3.65
3	1% change	- 3.45	- 3.76	- 7.59	2.78	.38	4.59	3.65
	5% change	- 3.59	- 3.90	- 7.24	2.84	.37	4.59	3.67
	10% change	- 3.76	- 4.09	- 6.81	2.91	.37	4.60	3.76
	CSU ID	1762500	1801800	1804500	1805400	1810000	1930000	
	Optimized	- 3.38	- 6.93	1.89	- .19	.05	4.78	3.78
4	1% change	- 3.41	- 7.00	1.91	- .17	.06	4.80	3.78
	5% change	- 3.54	- 7.28	1.98	- .08	.07	4.84	3.82
	10% change	- 3.71	- 7.62	2.07	.04	.08	4.90	3.96
	CSU ID	1762500	1801816	1802730	1804500	1810000	1930000	
	Optimized	- 4.23	- 3.19	- .70	4.58	- .15	4.54	3.93
5	1% change	- 4.27	- 3.22	- .69	4.61	- .16	4.56	3.93
	5% change	- 4.44	- 3.35	- .64	4.72	- .19	4.63	4.01
	10% change	- 4.66	- 3.51	- .57	4.86	- .23	4.72	4.26
	CSU ID	1762500	1800900	1801816	1804500	1810000	1930000	
	Optimized	- 3.83	.13	- 3.64	4.37	.01	3.88	4.19
6	1% change	- 3.87	.13	- 3.60	4.36	.01	3.88	4.19
	5% change	- 4.02	.14	- 3.39	4.33	.02	3.90	4.22
	10% change	- 4.22	.15	- 3.14	4.28	.03	3.91	4.30
	CSU ID	1762500	1801816	1804500	1805400	1810000	1930000	
	Optimized	- 3.61	- 3.63	3.62	.01	- .22	4.33	4.35
7	1% change	- 3.65	- 3.67	3.65	.04	- .22	4.34	4.36
	5% change	- 3.79	- 3.81	3.80	.14	- .22	4.36	4.40
	10% change	- 3.98	- 4.00	3.98	.26	- .22	4.39	4.54
	CSU ID	1762500	1800900	1802730	1804500	1810000	1930000	
	Optimized	- 4.79	- 5.71	- 1.98	4.40	.02	4.87	4.85
8	1% change	- 4.84	- 5.77	- 1.98	4.43	.02	4.89	4.85
	5% change	- 5.03	- 6.00	- 1.98	4.53	- .01	4.98	4.93
	10% change	- 5.27	- 6.28	- 1.98	4.65	- .04	5.09	5.17
	CSU ID	1762500	1801800	1801816	1802730	1810000	1930000	
	Optimized	- 2.72	- 9.58	- 1.00	1.29	.62	4.76	5.15
9	1% change	- 2.74	- 9.68	- .93	1.28	.62	4.77	5.15
	5% change	- 2.85	-10.06	- .66	1.24	.62	4.84	5.18
	10% change	- 2.99	-10.54	- .32	1.18	.61	4.92	5.29
	CSU ID	1762500	1801800	1802730	1805400	1810000	1930000	
	Optimized	- 2.96	- 8.75	.64	.04	.29	5.03	5.39
10	1% change	- 2.99	- 8.84	.66	.07	.29	5.04	5.39
	5% change	- 3.11	- 9.19	.72	.15	.32	5.07	5.43
	10% change	- 3.26	- 9.62	.80	.26	.35	5.12	5.57

TABLE 8 SENSITIVITY OF NUMBER OF YEARS FOR EVALUATION ACCORDING TO CHANGE OF COVARIANCE MATRIX (THE UPPER BASIN OF THE COLORADO RIVER)

Years for which data were not used				Combination of Sub-basins and Coefficients					Number of Years for Evaluation
			1762500	1801800	1801816	1804500	1810000	1930000	
----	----	----	-3.37	-5.45	-2.31	3.60	.07	4.51	2.90
1948	1951	1954	-3.26	-5.69	-2.01	3.32	.14	4.46	2.64
1948	1951	1956	-3.74	-6.51	- .67	2.64	.30	4.53	2.76
1948	1951	1958	-3.65	-4.44	-1.90	3.81	.06	4.33	2.53
1948	1951	1960	-3.46	-5.41	-2.02	3.30	.15	4.49	3.21
1948	1951	1963	-3.49	-4.48	-2.27	3.39	.14	4.39	3.20
1948	1954	1956	-3.44	-6.89	- .93	2.83	.25	4.52	2.50
1948	1954	1958	-3.36	-4.87	-2.18	3.92	.02	4.35	2.20
1948	1954	1960	-3.20	-5.72	-2.24	3.45	.11	4.48	2.75
1948	1954	1963	-3.25	-4.54	-2.50	3.59	.09	4.35	2.68
1948	1956	1958	-3.70	-5.17	-1.49	3.53	.11	4.40	2.69
1948	1956	1960	-3.59	-6.27	-1.28	2.95	.22	4.55	3.21
1948	1956	1963	-3.60	-5.50	-1.57	3.05	.21	4.47	3.22
1948	1958	1960	-3.57	-4.59	-2.19	4.00	.01	4.38	2.71
1948	1958	1963	-3.66	-2.79	-2.60	4.19	.01	4.17	2.63
1948	1960	1963	-3.43	-4.41	-2.54	3.53	.10	4.41	3.33
1951	1954	1956	-3.59	-7.53	- .18	2.74	.28	4.52	2.37
1951	1954	1958	-3.47	-4.96	-1.79	3.89	.04	4.31	2.00
1951	1954	1960	-3.27	-6.11	-1.83	3.50	.10	4.48	2.69
1951	1954	1963	-3.30	-5.21	-2.08	3.64	.08	4.38	2.69
1951	1956	1958	-3.90	-5.61	- .67	3.32	.17	4.37	2.36
1951	1956	1960	-3.76	-7.03	- .41	2.82	.26	4.55	3.01
1951	1956	1963	-3.74	-6.78	- .57	2.83	.26	4.54	3.09
1951	1958	1960	-3.69	-4.70	-1.73	3.91	.04	4.34	2.42
1951	1958	1963	-3.75	-3.11	-2.14	4.15	.00	4.16	2.41
1951	1960	1963	-3.49	-5.28	-2.00	3.54	.10	4.46	3.27
1954	1956	1958	-3.56	-6.05	-1.05	3.53	.11	4.40	2.05
1954	1956	1960	-3.45	-7.33	- .77	3.05	.20	4.55	2.58
1954	1956	1963	-3.44	-6.69	-1.01	3.15	.18	4.48	2.60
1954	1958	1960	-3.39	-5.10	-2.06	4.06	-.01	4.35	2.15
1954	1958	1963	-3.48	-3.28	-2.45	4.35	-.05	4.14	2.03
1954	1960	1963	-3.24	-5.23	-2.30	3.77	.05	4.40	2.80
1956	1958	1960	-3.73	-5.45	-1.35	3.68	.08	4.41	2.62
1956	1958	1963	-3.74	-3.74	-1.95	4.01	.02	4.24	2.62
1958	1960	1963	-3.66	-3.25	-2.43	4.32	-.04	4.21	2.60

Chapter VI

CONCLUSION

Suitability of basins for weather modification over the whole Upper Colorado River Basin was discussed from a hydrologic standpoint.

The relationship between precipitation and spring runoff with greater than 0.90 correlation coefficient was obtained for 365 sets by applying a multiple linear regression analysis, the independent variables being winter and spring precipitation. Using this relationship, the increase of spring runoff due to a 10 percent increase of winter precipitation was calculated and used as a criterion to discuss optimal water yield. The following watersheds are those where a relatively large amount of increase of runoff can be expected in order:

(a) San Juan Mountains,

(b) Upper reach of the Yampa River and its tributaries,

(c) Headwater of the Green River,

(d) Upper basin of the Colorado River,

(e) Upper basins of Uinta River, Lake Fork, and Rock Creek, and

(f) Headwaters of the Rafael River.

By applying the two-sample u-test, the number of years for evaluation of weather modification attainment for each basin was discussed. Though results show some variability between watersheds separated by a very short distance, the following basins lead to a smaller number of years needed for evaluation on the average:

(a) Upper reach of the Yampa River and its tributaries,

(b) Headwater of the Green River,

(c) Upper basin of the Colorado River,

(d) Upper basins of Uinta River, Lake Fork, and Rock Creek, and

(e) San Juan Mountains.

These results show that the upper reach of the Yampa River and its tributaries; the headwaters of the Green River; and the upper basins of Uinta River, Lake Fork, and Rock Creek are suitable, in addition to the two pilot-areas--the San Juan Mountains and the Upper Basin of the Colorado River.*

Furthermore, the number of years for evaluation was calculated for certain combinations of basins in the pilot area by using a new variable that is a linear combination of a given number of runoff variables from individual sub-basins. This was done in order to select the most desirable combination of basins for the planned experiment. It was found that particular gages play a particularly important role in keeping the number of years needed for evaluation to a minimum. They are in the

(a) San Juan Mountains

1077015	Navajo River at Edith
1077250	Rio Blanco near Pagosa Springs
1371555	Uncompahgre River near Ridgway

(b) the Upper Basin of the Colorado River

1762500	East Fork Troublesome Creek near Troublesome
1810000	Willow Creek below Willow Creek Reservoir
1930000	North Inlet at Grand Lake

However, the study shows that there exist a great deal of latitude in the actual choice of the stations with little loss of efficiency in evaluation. This fact is probably the most important result of this study.

It also was found the minimum number of years in the San Juan Mountains was six, and in the Upper Basin of the Colorado River Basin was three. It must be remembered that these results hold under the assumption of a uniform 10% increase in winter precipitation in both pilot areas. If the increase is greater the number of years decreases approximately at a quadratic rate.

At this point, no physical meaning is assigned to the α_i's in equation (3). It may be desirable to consider the meaning of the α_i's in a further study.

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*Since the initiation of this study the plans of the Bureau were modified. Currently (45) only one area is considered: the San Juan Mountains region.

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APPENDICES

A and B

APPENDIX A

List of Precipitation Stations

The numbers in the tables of the recorded data indicate the number of missing monthly data. However, the number "9" indicates that the number of missing monthly data is 9, 10, or 11 and the "*" indicates that there is no monthly data at all.

CSU NO	BUREAU NO	NAME	LATITUDE	LONGITUDE	ELEVATION	RECORDING BEGAN-ENDED	CONTINUOUS RECORDINGS	188 0123456789	189 0123456789	190 0123456789	191 0123456789	192 0123456789	193 0123456789	194 0123456789	195 0123456789	196 012345
10114000	37.0000	PAHREAH	37.15. 0	111.57. 0	4000.0	1895-1899	1896-1899	**********	*****10000	**********	**********	**********	**********	**********	**********	******
10180500	37.3847	HENRIEVILLE	37.34. 0	112. 0. 0	6000.0	1963-1965	1964-1965	**********	**********	**********	**********	**********	**********	**********	**********	***600
10198000	37.8847	TROPIC	37.37. 0	112. 6. 0	6290.0	1889-1965	1953-1965	*********7	5000094720	0000050000	3000062004	470093175*	*****30000	0003000000	3310000000	000003
10200000	2.4849	LEES FERRY	36.52. 0	111.35. 0	3141.0	1917-1965	1944-1965	**********	**********	**********	*******257	7900002000	000000015*	***4000000	0000000000	000000
10400000	2.9114	WAHWEAP	36.59. 0	111.19. 0	3720.0	1961-1965	1962-1965	**********	**********	**********	**********	**********	**********	**********	**********	*70000
10400002	2.2099	COPPER MINE TRAD	36.38. 0	111.25. 0	5390.0	1941-1965	1952-1955	**********	**********	**********	**********	**********	**********	*300000000	020000****	******
10400003	2.4520	KAIBITO	36.36. 0	111. 5. 0	6000.0	1950-1960	1951-1960	**********	**********	**********	**********	**********	**********	**********	3000000000	0*****
10400004	37.6676	NAVAJO MOUNTAIN	37. 1. 0	110.48. 0	6020.0	1957-1965	1959-1965	**********	**********	**********	**********	**********	**********	**********	*******320	000000
10590000	37.3232	GLEN CANYON CITY	37. 5. 0	111.43. 0	4180.0	1962-1965	1963-1965	**********	**********	**********	**********	**********	**********	**********	**********	**9000
10700001	37.5810	MONUMENT VALLEY	37. 0. 0	110.12. 0	5210.0	1956-1959	1958-1959	**********	**********	**********	**********	**********	**********	**********	******7300	******
10702000	37.5582	MEXICAN HAT	37. 9. 0	109.52. 0	4230.0	1946-1965	1953-1965	**********	**********	**********	**********	**********	**********	******3000	1130002000	000000
10706000	2.2545	DINNEHOTSO	36.51. 0	109.51. 0	5180.0	1955-1959	1956-1959	**********	**********	**********	**********	**********	**********	**********	*****30000	******
10706002	2.5204	MANY FARMS	36.21. 0	109.37. 0	5310.0	1951-1965	1952-1965	**********	**********	**********	**********	**********	**********	**********	*300004000	000000
10706003	2.0808	BLACK MOUNTAIN M	36. 7. 0	109.52. 0	6350.0	1957-1965	1958-1965	**********	**********	**********	**********	**********	**********	**********	*********8	000000
10706004	2.2147	COTTON WOOD INDI	36. 4. 0	109.53. 0	6050.0	1956-1958	1957-1958	**********	**********	**********	**********	**********	**********	**********	*******00*	******
10706005	2.1634	CHINLE	36. 9. 0	109.32. 0	5538.0	1909-1965	1942-1965	**********	**********	*********2	0000000000	200008905*	*****90330	0200000001	0000000000	000000
10706019	2.5129	LUKACHUKAI	36.26. 0	109.14. 0	6480.0	1915-1964	1962-1964	**********	**********	**********	*****31***	**********	**********	**********	*000000000	32000*
10706200	2.4574	KAYENTA	36.44. 0	110.16. 0	5665.0	1918-1965	1965-1965	**********	**********	**********	*******068	5000000000	0000000007	1*70252000	0000000000	000052
10714000	37.0788	BLUFF	37.17. 0	109.33. 0	4315.0	1911-1965	1928-1965	**********	**********	**********	*640006793	0078115200	0000000000	0000000000	0000040000	000003
10714001	37.0738	BLANDING	37.37. 0	109.28. 0	6036.0	1905-1965	1912-1965	**********	**********	*****20000	0*00000000	0000000000	0000000000	0000000000	0000000030	000000
10716000	37.0137	ANETH	37.13. 0	109.11. 0	4650.0	1900-1962	1962-1962	**********	**********	70000000**	3202******	**********	**********	**********	**********	*92***
10716001	5.0000	DOVE CREEK	37.46. 0	108.54. 0	5678.0	1916-1921	1917-1921	**********	**********	**********	******4000	00********	**********	**********	**********	******
10716002	5.0341	ATKINSON RANCH	37.36. 0	108.53. 0	7000.0	1948-1949	1949-1949	**********	**********	**********	**********	**********	**********	********7*	**********	******
10716004	37.5795	MONTEZUMA CREEK	37.43. 0	109. 5. 0	6790.0	1946-1956	1947-1956	**********	**********	**********	**********	**********	**********	******6000	0000000***	******
10716005	37.1708	CEDAR POINT	37.43. 0	109. 5. 0	6780.0	1952-1965	1952-1965	**********	**********	**********	**********	**********	**********	**********	**00000000	000000
10716006	37.0000	LOCKERBY	37.47. 0	109. 4. 0	7300.0	1917-1926	1924-1926	**********	**********	**********	*******300	00001*****	**********	**********	**********	******
10716007	5.5970	NORTHDALE	37.49. 0	109. 1. 0	6693.0	1931-1965	1932-1965	**********	**********	**********	**********	**********	*300000000	0000000000	0000000000	000000
10716008	37.0000	VERDURE	37.47. 0	109.21. 0	6800.0	1904-1908	1908-1908	**********	**********	******356*	**********	**********	**********	**********	**********	******
10716350	37.5805	MONTICELLO	37.52. 0	109.21. 0	7066.0	1902-1965	1953-1965	**********	**********	**30032463	*300000000	17*****900	0000000000	0000000012	0520000000	000000
10718001	2.8458	TEEC NOS POC	36.56. 0	109. 0. 0	5180.0	1962-1965	1963-1965	**********	**********	**********	**********	**********	**********	**********	**********	**8000
10718301	5.6591	PLEASANT VIEW 2W	37.35. 0	108.48. 0	7000.0	1950-1951	1951-1951	**********	**********	**********	**********	**********	**********	**********	74********	******
10718302	5.9275	YELLOW JACKET IN	37.33. 0	108.44. 0	6858.0	1962-1965	1963-1965	**********	**********	**********	**********	**********	**********	**********	**********	**8000
10718600	5.1886	CORTEZ	37.21. 0	108.34. 0	6177.0	1931-1965	1932-1965	**********	**********	**********	**********	**********	*300000000	0000000000	0000000000	000000
10720000	5.5531	MESA VERDE NATIO	37.12. 0	108.29. 0	7070.0	1922-1965	1923-1965	**********	**********	**********	**********	**90000000	0000000000	0000000000	0000000000	000000
10720300	5.5327	MANCOS	37.21. 0	108.18. 0	7015.0	1898-1965	1948-1965	**********	********30	0050000000	0000000000	9*********	**********	*******900	0000000000	000000
10724000	25.8284	SHIPROCK 1 E	36.47. 0	108.39. 0	4974.0	1926-1965	1954-1965	**********	**********	**********	**********	******3000	0000000011	007*900000	0010000000	002700
10726151	25.6098	NEWCOMB	36.17. 0	108.42. 0	5565.0	1952-1965	1952-1965	**********	**********	**********	**********	**********	**********	**********	**00000000	000000
10726154	25.9657	WESTBROOK RANCH	35.56. 0	108.12. 0	6600.0	1948-1952	1952-1952	**********	**********	**********	**********	**********	**********	********91	003*******	******
10726155	25.9485	OTIS	36.19. 0	107.52. 0	6880.0	1957-1965	1959-1965	**********	**********	**********	**********	**********	**********	**********	*******700	000000
10726156	25.0000	NAGEEZI	36.16. 0	107.45. 0	6800.0	1949-1951	1951-1951	**********	**********	**********	**********	**********	**********	**********	07********	******
10726157	25.5290	LYBROOK	36.14. 0	107.35. 0	7160.0	1951-1965	1956-1965	**********	**********	**********	**********	**********	**********	**********	*400060000	000000
10726158	25.1647	CHACO CANYON NAT	36. 4. 0	107.58. 0	6125.0	1932-1965	1950-1965	**********	**********	**********	**********	**********	**90000000	0112030002	0000000000	000000
10726159	25.6900	PITT RANCH	35.48. 0	108. 1. 0	6460.0	1952-1965	1952-1965	**********	**********	**********	**********	**********	**********	**********	**00000000	000000
10726161	25.2219	CROWNPOINT	35.41. 0	108. 9. 0	6978.0	1914-1965	1955-1965	**********	**********	**********	****300000	0000000000	0000000000	0000000002	0000300000	000000
10726600	25.5685	MEXICAN SPRINGS	35.48. 0	108.50. 0	6437.0	1934-1965	1956-1965	**********	**********	**********	**********	**********	****700000	00039125**	0000000000	000000
10726750	25.8919	TOHATCHI	35.51. 0	108.46. 0	6800.0	1913-1965	1958-1965	**********	**********	**********	***3000*00	9393000000	0001000010	0002869012	0000000000	000000
10728000	25.3340	FRUITLAND	36.44. 0	108.24. 0	5165.0	1891-1965	1954-1965	**********	*3000000*0	0000000000	0000000000	000009****	********90	0120400001	0000000000	002300
10730000	25.3128	FARMINGTON FAA A	36.45. 0	108.45. 0	5495.0	1941-1965	1942-1965	**********	**********	**********	**********	**********	**********	*000000000	0000000000	000000
10733600	5.4616	KLINE 3W	37. 7. 0	108.11. 0	6619.0	1941-1949	1949-1949	**********	**********	**********	**********	**********	**********	*000000004	**********	******
10733601	5.0000	KLINE 9WNW	37.11. 0	108.15. 0	7000.0	1944-1946	1946-1946	**********	**********	**********	**********	**********	**********	****301***	**********	******
10733602	5.0000	ALKALI CREEK	37.12. 0	108.10. 0	7000.0	1945-1947	1947-1947	**********	**********	**********	**********	**********	**********	*****504**	**********	******
10733603	5.3016	FORT LEWIS	37.14. 0	108. 3. 0	7595.0	1880-1965	1955-1965	4300100000	01********	*********9	*900000000	0000000000	0000000000	0000000000	0000100000	000000
10734000	25.3134	FARMINGTON	36.45. 0	108.10. 0	5395.0	1914-1965	1933-1965	**********	**********	**********	****300000	0000000000	0090000000	0000000000	0000000000	000003
10734040	25.0692	AZTEC RUINS NAT	36.50. 0	108. 0. 0	5640.0	1895-1965	1911-1965	**********	*****30000	0000******	3000000000	0000000000	0000000000	0000000000	0000000000	000000
10734150	5.0000	FALFA	37.13. 0	107.45. 0	6954.0	1945-1945	1945-1945	**********	**********	**********	**********	**********	**********	*****3****	**********	******
10734360	5.2432	DURANGO	37.17. 0	107.53. 0	6554.0	1889-1965	1895-1965	*********3	2****00000	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000	000000
10734560	5.8154	TACOMA	37.31. 0	107.47. 0	7300.0	1906-1965	1952-1965	**********	**********	******9100	0000000000	0000000000	09********	**********	**00000000	000000
10734561	5.2424	ELECTRA LAKE	37.33. 0	107.49. 0	8398.0	1959-1965	1960-1965	**********	**********	**********	**********	**********	**********	**********	*********1	000000
10734640	5.0000	SAVAGE BASIN	37.55. 0	107.44. 0	11500.0	1915-1931	1925-1931	**********	**********	**********	*****41000	0300200000	00********	**********	**********	******
10734641	5.1386	CASCADE	37.40. 0	107.48. 0	8853.0	1906-1957	1908-1957	**********	**********	******9100	0020000000	0000000000	0000000000	0000000000	00000000**	******
10734680	5.7656	SILVERTON	37.48. 0	107.40. 0	9322.0	1906-1965	1958-1965	**********	**********	******4100	0000000000	0000000000	0000000000	0000000000	0000000012	000000
10734681	5.0000	SILVERTON NO. 1	37.48. 0	107.40. 0	9401.0	1905-1910	1910-1910	**********	**********	*****30107	3*********	**********	**********	**********	**********	******
10734720	5.0000	GLADSTONE	37.53. 0	107.39. 0	10400.0	1906-1917	1917-1917	**********	**********	******9100	10700001**	**********	**********	**********	**********	******
10738000	25.1063	BLOOMFIELD 3 SE	36.40. 0	107.58. 0	5794.0	1891-1965	1958-1965	**********	*300009***	****300000	0000000000	0000000000	0030000000	0002001893	0000000000	000000
10744000	25.3706	GRENVILLE	36.30. 0	107.37. 0	5990.0	1944-1962	1952-1962	**********	**********	**********	**********	**********	**********	****300002	1100000000	000***
10744002	25.6458	OTERO	36.16. 0	107.23. 0	6600.0	1953-1957	1954-1957	**********	**********	**********	**********	**********	**********	**********	***40000**	******
10746000	25.6081	NAVAJO DAM	36.49. 0	107.37. 0	5770.0	1963-1965	1964-1965	**********	**********	**********	**********	**********	**********	**********	**********	***800
10750000	25.3588	GOBERNADOR	36.42. 0	107.24. 0	6710.0	1955-1959	1956-1959	**********	**********	**********	**********	**********	**********	**********	*****9405*	******
10750001	25.3589	GOBERNADOR 7W	36.41. 0	107.23. 0	7200.0	1925-1955	1955-1955	**********	**********	**********	**********	*****9*0**	**80000000	0000000100	010008****	******
10756000	25.0000	ROSA NEAR	36.53. 0	107.35. 0	6500.0	1930-1931	1931-1931	**********	**********	**********	**********	**********	30********	**********	**********	******
10758200	5.4250	IGNACIO 1 N	37. 8. 0	107.38. 0	6424.0	1909-1965	1951-1965	**********	**********	*********9	9***300000	0000000000	0000000000	0000000010	2000000000	000000
10758400	5.8582	VALLECITO DAM	37.24. 0	107.33. 0	7650.0	1943-1965	1943-1965	**********	**********	**********	**********	**********	**********	***0000000	0000000000	000000
10762000	5.0307	ARBOLES	37. 1. 0	107.25. 0	6175.0	1958-1963	1959-1963	**********	**********	**********	**********	**********	**********	**********	********30	0000**
10762001	5.0000	ARBOLES	37. 1. 0	107.23. 0	6013.0	1891-1894	1894-1894	**********	*7104*****	**********	**********	**********	**********	**********	**********	******
10764200	5.1570	CHIMNEY ROCK	37.12. 0	107.19. 0	6550.0	1961-1962	1962-1962	**********	**********	**********	**********	**********	**********	**********	**********	*99***

Appendix A continued

CSU NO	BUREAU NO	NAME	LATITUDE	LONGITUDE	ELEVATION	RECORDING BEGAN-ENDED	CONTINUOUS RECORDINGS	188 0123456789	189 0123456789	190 0123456789	191 0123456789	192 0123456789	193 0123456789	194 0123456789	195 0123456789	196 012345
10764201	5.7928	STATE TURKEY EXP	37.13. 0	107.16. 0	6900.0	1944-1961	1961-1961	**********	**********	**********	**********	**********	**********	****910000	0010000000	03****
10770000	25.2608	DULCE	36.57. 0	107. 0. 0	6940.0	1906-1965	1946-1965	**********	**********	******3000	0000000000	0000000000	0000000000	0**4790000	0000000000	000000
10770300	5.0000	CHROMO	37. 4. 0	106.47. 0	7385.0	1890-1912	1912-1912	**********	70********	******3000	011*******	**********	**********	**********	**********	******
10774000	5.6258	PAGOSA SPRINGS	37.16. 0	107. 1. 0	7118.0	1882-1965	1953-1965	**0*******	90********	*******300	0000007***	**********	*********6	0000000001	1110000000	000000
10776000	5.0000	PAGOSA SPRINGS I	37.23. 0	106.57. 0	7738.0	1928-1937	1937-1937	**********	**********	**********	**********	*********1	000*7005**	**********	**********	******
10776001	5.6271	PALISADE LAKE 2	37.38. 0	107.10. 0	7721.0	1917-1965	1948-1965	**********	**********	**********	*******900	000000003*	**********	*******900	0000000000	000000
10778600	5.9183	WOLF CREEK PASS	37.29. 0	106.52. 0	9425.0	1936-1965	1958-1965	**********	**********	**********	**********	**********	******9599	0000000000	0210000400	000000
10810001	37.2592	ESCALANTE	37.46. 0	111.38. 0	5750.0	1901-1965	1959-1965	**********	**********	*9000*9000	00****8000	3700000000	0000000000	0006200000	0000000439	000000
10820250	37.0849	BOULDER	37.55. 0	112.29. 0	6580.0	1954-1965	1955-1965	**********	**********	**********	**********	**********	**********	**********	****904000	000000
11040000	37.3968	HITE	37.49. 0	110.28. 0	3470.0	1948-1954	1949-1954	**********	**********	**********	**********	**********	**********	********40	00000*****	******
11150000	37.6053	NATURAL BRIDGES	37.37. 0	109.59. 0	6500.0	1965-1965	1965-1965	**********	**********	**********	**********	**********	**********	**********	**********	*****2
11409000	37.3611	HANKSVILLE FAA A	38.25. 0	110.41. 0	4456.0	1910-1965	1945-1965	**********	**********	**********	3035300000	0000000000	0000000000	0007500000	0000000000	000000
11418000	37.0000	WILLOW SPRINGS C	38.43. 0	111.17. 0	5560.0	1941-1942	1942-1942	**********	**********	**********	**********	**********	**********	*36*******	**********	******
11418200	37.2484	EMERY	38.55. 0	111.15. 0	6260.0	1901-1965	1955-1965	**********	**********	*300000000	0000000000	0310000000	0000000000	0000000000	0000000000	000050
11418800	37.0000	YELLOW PINE	39. 0. 0	111.20. 0	8380.0	1916-1916	1916-1916	**********	**********	**********	******0***	**********	**********	**********	**********	******
11436000	37.0000	GILES	38.22. 0	110.51. 0	4460.0	1895-1906	1896-1906	**********	*****30000	0000000***	**********	**********	**********	**********	**********	******
11454000	37.3646	FRUITA	38.17. 0	111.15. 0	5418.0	1938-1965	1944-1965	**********	**********	**********	**********	**********	********90	5000000200	0000004000	000000
11454001	37.0000	TEASDALE	38.14. 0	111.21. 0	7100.0	1917-1919	1919-1919	**********	**********	**********	*******334	**********	**********	**********	**********	******
11493300	37.5148	LOA	38.24. 0	111.37. 0	7045.0	1892-1965	1936-1965	**********	**30000000	0000000000	089*******	**30000060	4010410000	0000000000	0000000000	000000
11463001	37.0000	ELKHORN FISH LAK	38.27. 0	111.28. 0	8600.0	1922-1928	1924-1924	**********	**********	**********	**********	**0*8677**	**********	**********	**********	******
11601309	37.2798	FERRON	39. 6. 0	111. 8. 0	5925.0	1952-1965	1952-1965	**********	**********	**********	**********	**********	**********	**********	**00004000	000000
11601425	37.1214	CASTLE DALE	39.13. 0	111. 1. 0	5675.0	1899-1965	1957-1965	**********	*********3	0000000000	0000000000	0000000000	0000000000	0006**6***	0110043*00	000000
11605000	37.3618	GREEN RIVER AVIA	39. 0. 0	110. 9. 0	4059.0	1891-1965	1948-1965	**********	*04406*0**	0000004910	0000005000	0000000000	40********	*******300	0000000000	000000
11607000	37.9429	WOODSIDE	39.16. 0	110.21. 0	4640.0	1912-1958	1958-1958	**********	**********	**********	**30554***	**********	**********	*0039*****	700000539*	******
11607001	37.8474	SUNNYSIDE	39.34. 0	110.22. 0	6660.0	1920-1965	1965-1965	**********	**********	**********	**********	3000711010	**********	**********	********40	0005**
11607003	37.0090	VICTOR LAKE	39.24. 0	110.42. 0	5250.0	1913-1922	1922-1922	**********	**********	**********	***3060000	001*******	**********	**********	**********	******
11607004	37.0000	DESERT LAKE	39.22. 0	110.44. 0	5600.0	1911-1911	1911-1911	**********	**********	**********	*9********	**********	**********	**********	**********	******
11607005	37.0000	WELLINGTON	39.32. 0	110.44. 0	5450.0	1900-1909	1909-1909	**********	**********	3000244978	**********	**********	**********	**********	**********	******
11607100	37.3896	HIAWATHA	39.29. 0	111. 1. 0	7230.0	1917-1965	1923-1965	**********	**********	**********	*******100	0930000000	0000000000	0000000000	0000000000	000000
11607150	37.7015	PRICE GAME FARM	39.37. 0	110.50. 0	5580.0	1911-1965	1944-1965	**********	**********	**********	*300602328	0000000000	0000000000	0005000000	0000000000	000000
11607151	37.7724	SCOFIELD DAM	39.47. 0	111. 7. 0	7630.0	1950-1965	1954-1965	**********	**********	**********	**********	**********	**********	**********	4924000000	000000
11607200	37.0000	CASTLE GATE	39.43. 0	110.52. 0	6000.0	1891-1896	1896-1896	**********	*0*1166***	**********	**********	**********	**********	**********	**********	******
11607400	37.7959	SOLDIER SUMMIT	39.55. 0	111. 5. 0	7460.0	1893-1960	1960-1960	**********	***7000010	10393000**	***0****94	5588122600	4000000000	0000000000	2791006*00	3*****
11607601	37.1472	CLEAR CREEK	39.39. 0	111. 9. 0	8300.0	1936-1965	1955-1965	**********	**********	**********	**********	**********	******1000	0000000000	0000500000	000000
11609300	37.6340	NUTTERS RANCH	39.48. 0	110.15. 0	5880.0	1963-1965	1954-1965	**********	**********	**********	**********	**********	**********	**********	**********	***900
11614001	37.0810	BONANZA PUMPING	40. 2. 0	109. 7. 0	5700.0	1960-1965	1961-1965	**********	**********	**********	**********	**********	**********	**********	**********	800000
11615000	37.0000	WATSON	39.51. 0	109.11. 0	6210.0	1911-1927	1912-1927	**********	**********	**********	*750000000	0000000***	**********	**********	**********	******
11615001	37.0000	DRAGON	39.47. 0	109. 6. 0	5890.0	1908-1909	1909-1909	**********	**********	********96	**********	**********	**********	**********	**********	******
11615002	5.0354	ARTESIA 2E	40.14. 0	108.58. 0	5921.0	1949-1965	1965-1965	**********	**********	**********	**********	**********	**********	********91	0*********	***904
11615004	5.6832	RANGELY	40. 5. 0	108.47. 0	5216.0	1894-1965	1953-1965	**********	****900013	00007*9000	043*******	**********	**********	**********	**20000000	000000
11615005	5.0000	SKULL CREEK	40.15. 0	108.39. 0	5700.0	1941-1944	1944-1944	**********	**********	**********	**********	**********	**********	*1102*****	**********	******
11615150	5.5048	LITTLE HILLS	40. 0. 0	109.12. 0	6148.0	1946-1965	1947-1965	**********	**********	**********	**********	**********	**********	******9004	0000000000	000000
11615201	5.5499	MEEKER 10NW	40. 8. 0	107.59. 0	6425.0	1930-1953	1953-1953	**********	**********	**********	**********	**********	4000000000	0000000004	5401******	******
11615202	5.5484	MEEKER	40. 2. 0	107.54. 0	6242.0	1891-1965	1942-1965	**********	*300000000	0000000000	0000000000	000000039*	**********	*200000000	0000000000	000000
11615203	5.0000	MEEKER NO. 3	40. 4. 0	107.55. 0	6192.0	1891-1926	1892-1926	**********	*300000000	0000000000	0000000000	0000000***	**********	**********	**********	******
11615550	5.5409	MARVINE	40. 0. 0	107.33. 0	7200.0	1947-1965	1955-1965	**********	**********	**********	**********	**********	**********	*******920	0000000000	000050
11617020	37.7395	ROOSEVELT	40.18. 0	109.59. 0	5094.0	1940-1965	1951-1965	**********	**********	**********	**********	**********	**********	2000000002	1000000000	000000
11617021	37.6123	NEOLA	40.25. 0	110. 3. 0	6000.0	1956-1965	1957-1965	**********	**********	**********	**********	**********	**********	**********	******7000	000000
11617040	37.0000	MIDDLE CAMP	40.29. 0	110. 0. 0	8600.0	1941-1942	1942-1942	**********	**********	**********	**********	**********	**********	**6*******	**********	******
11617041	37.0000	DRY GULCH RS	40.32. 0	110.13. 0	7880.0	1916-1929	1920-1929	**********	**********	**********	******4321	3544455145	**********	**********	**********	******
11617030	37.2996	FORT DUCHESNE	40.17. 0	109.51. 0	4990.0	1888-1965	1921-1965	********20	0000000000	0000000000	0000002305	2000000000	0000000000	0000000000	0000000000	000000
11617060	37.4927	LA POINT	40.24. 0	109.48. 0	5500.0	1944-1960	1944-1960	**********	**********	**********	**********	**********	**********	****32020*	5000000000	0*****
11617061	37.0000	WHITE ROCKS	40.21. 0	109.55. 0	5470.0	1912-1914	1913-1914	**********	**********	**********	**300*****	**********	**********	**********	**********	******
11617062	37.0000	HAYDEN	40. 6. 0	109.50. 0	6000.0	1915-1917	1917-1917	**********	**********	**********	*****311**	**********	**********	**********	**********	******
11617140	37.2429	ELKHORN ASHLEY R	40.33. 0	109.57. 0	6850.0	1910-1965	1937-1955	**********	**********	**********	3000549703	7000000000	0300000000	0000000000	000000****	******
11617250	37.5969	MYTON	40.12. 0	110. 4. 0	5084.0	1915-1965	1955-1965	**********	**********	**********	*****90000	0000000000	0000000000	0000000000	0000000000	000005
11617270	37.0074	ALTAMONT	40.19. 0	110.14. 0	6180.0	1952-1965	1955-1965	**********	**********	**********	**********	**********	**********	**********	**00000000	000009
11617271	37.0000	MOUNTAIN HOME	40.24. 0	110.24. 0	6750.0	1912-1918	1918-1918	**********	**********	**********	**7031090*	**********	**********	**********	**********	******
11617310	37.9679	YELLOWSTONE RS	40.33. 0	110.20. 0	7700.0	1931-1947	1942-1947	**********	**********	**********	**********	**********	*796678677	6600000***	**********	******
11617350	37.5815	MOON LAKE	40.34. 0	110.30. 0	8150.0	1935-1965	1965-1965	**********	**********	**********	**********	**********	*****80000	0000000000	2921004975	766993
11617400	37.2253	DUCHESNE	40.10. 0	110.24. 0	5515.0	1906-1965	1907-1965	**********	**********	******3000	0000000000	0000000000	0000000000	0000000000	0000000000	000000
11617530	37.3056	FRUITLAND	40.13. 0	110.51. 0	5520.0	1910-1965	1965-1965	**********	**********	**********	5000121141	3000000000	5******600	0000004113	200*******	***049
11617630	37.8370	STRAWBERRY HWY 5	40.15. 0	111. 7. 0	7700.0	1962-1965	1953-1965	*****8****	**********	**********	**********	**********	**********	**********	**********	**7000
11617631	37.8476	STRAWBERRY RES.	40.10. 0	111.11. 0	7605.0	1956-1965	1955-1965	**********	**********	**********	**********	**********	**********	**********	*******776	667687
11617634	37.8371	STRAWBERRY JUNCT	40.14. 0	111.11. 0	7645.0	1954-1954	1954-1954	**********	**********	**********	**********	**********	**********	**********	****7*****	******
11617850	37.3626	HANNA	40.26. 0	110.49. 0	6780.0	1952-1965	1953-1965	**********	**********	**********	**********	**********	**********	**********	**90000000	000000
11618000	37.6508	OURAY	40. 8. 0	109.39. 0	4760.0	1943-1965	1954-1965	**********	**********	**********	**********	**********	**********	***43*****	******1000	000000
11622001	37.9111	VERNAL AIRPORT	40.27. 0	109.31. 0	5290.0	1895-1965	1953-1965	**********	*****10000	0000*00170	0004960007	0000000000	0000000000	000310370*	0010000000	000000
11622150	37.0000	MASSEYS RANCH	40.37. 0	109.47. 0	7300.0	1938-1943	1940-1943	**********	**********	**********	**********	**********	**********	0000******	**********	******
11623000	37.4342	JENSEN	40.22. 0	109.21. 0	4720.0	1916-1965	1953-1965	**********	**********	**********	******2374	1003030049	1410000000	0000000000	0000000000	001000
11626001	37.0000	TROUT CREEK RS	40.46. 0	109.38. 0	9200.0	1910-1930	1930-1930	**********	**********	**********	8378856988	8009787898	3*********	**********	**********	******
11627000	37.2172	DINOSAUR NATL MO	40.25. 0	109.20. 0	4880.0	1941-1957	1948-1957	**********	**********	**********	**********	**********	**********	*43**89700	0000000***	******
11627001	37.2173	DINOSAUR NATL MO	40.26. 0	109.18. 0	4770.0	1958-1965	1959-1965	**********	**********	**********	**********	**********	**********	**********	********60	000000
11632000	5.2880	FERNDALE RANCH	40.47. 0	107.59. 0	7000.0	1941-1960	1950-1960	**********	**********	**********	**********	**********	**********	*455445545	7685546667	9*****
11632030	5.3538	GREAT DIVIDE	40.47. 0	107.50. 0	6970.0	1948-1951	1951-1951	**********	**********	**********	**********	**********	**********	********30	01********	******

Appendix A continued

CSU NO	BUREAU NO	NAME	LATITUDE	LONGITUDE	ELEVATION	RECORDING BEGAN-ENDED	CONTINUOUS RECORDING	188 0123456789	189 0123456789	190 0123456789	191 0123456789	192 0123456789	193 0123456789	194 0123456789	195 0123456789	196 012345
11632000	42.2610	DIXON	41. 2. 0	107.32. 0	6360.0	1909-1945	1950-1965	**********	**********	*********9	**********	**50000000	0000000000	0000000001	0000000000	000000
11632201	42.0000	BATTLE MOUNTAIN	41. 2. 0	107.17. 0	7300.0	1910-1912	1912-1912	**********	**********	**********	507*******	**********	**********	**********	**********	******
11632300	42.0000	RAMBLER	41.10. 0	107. 1. 0	9733.0	1905-1911	1911-1911	**********	**********	*****76***	59********	**********	**********	**********	**********	******
11632430	5.8100	SUNBEAM 7SW	40.30. 0	108.16. 0	5681.0	1927-1951	1951-1951	**********	**********	**********	**********	*******600	0000000000	0000000100	1*********	******
11632432	5.5446	MAYBELL	40.31. 0	108. 5. 0	5970.0	1958-1965	1959-1965	**********	**********	**********	**********	**********	**********	**********	********90	000000
11632433	5.0000	LAY	40.32. 0	107.53. 0	6172.0	1890-1935	1901-1935	**********	30000000*9	1000000000	0000000000	0000000000	0000000***	**********	**********	******
11632490	5.3738	HAMILTON	40.22. 0	107.37. 0	6230.0	1947-1965	1948-1965	**********	**********	**********	**********	**********	**********	*******900	0000000000	000000
11632520	5.0000	PAGODA	40.19. 0	107.20. 0	7040.0	1890-1912	1912-1912	**********	*400000000	0041010111	12********	**********	**********	**********	**********	******
11632521	5.9143	WILLOW CREEK 4SE	40.18. 0	107.16. 0	7250.0	1930-1948	1944-1944	**********	**********	**********	**********	**********	3105340000	000000029*	**********	******
11632522	5.0000	DUNKLEY	40.18. 0	107.11. 0	7400.0	1906-1908	1908-1908	**********	**********	******442*	**********	**********	**********	**********	**********	******
11632570	5.1928	CRAIG	40.31. 0	107.33. 0	6247.0	1936-1965	1954-1965	**********	**********	**********	**********	**********	******7000	0300000000	0001000000	000000
11632610	5.3867	HAYDEN	40.30. 0	107.15. 0	6337.0	1909-1965	1953-1965	**********	**********	*********3	9**3000***	3000530053	5800000000	0000000000	0010000000	000000
11632690	5.6797	PYRAMID	40.14. 0	107. 6. 0	8084.0	1911-1965	1948-1965	**********	**********	**********	*22*****9A	000040000*	**********	*******900	0000000000	000000
11632800	5.0000	HAHNS PEAK	40.49. 0	106.56. 0	8153.0	1905-1908	1908-1908	**********	**********	*****7156*	**********	**********	**********	**********	**********	******
11632801	5.1792	COLUMBINE	40.51. 0	106.58. 0	8609.0	1909-1942	1918-1942	**********	**********	**********	0000005100	0000000000	0000000000	00********	**********	******
11632850	5.7936	STEAMBOAT SPRING	40.30. 0	106.50. 0	6770.0	1891-1965	1931-1965	**********	*900050009	********90	0000000000	0000000000	7000000000	8000000000	0000000000	000000
11632851	5.6811	RABBIT EARS PASS	40.22. 0	106.43. 0	9340.0	1948-1948	1948-1948	**********	**********	**********	**********	**********	**********	********9*	**********	******
11632940	5.9265	YAMPA	40. 9. 0	106.52. 0	7890.0	1909-1965	1948-1965	**********	**********	*********3	0000500004	*90*******	**********	**3****900	0000000000	000000
11634000	5.0000	LODORE	40.39. 0	108.39. 0	5555.0	1910-1912	1912-1912	**********	**********	**********	*56*******	**********	**********	**********	**********	******
11634001	5.3629	GREYSTONE	40.37. 0	108.40. 0	6600.0	1937-1962	1962-1962	**********	**********	**********	**********	**********	*******500	000000002*	*********8	158***
11634002	5.3975	HIAWATHA	40.59. 0	108.37. 0	7100.0	1953-1957	1957-1957	**********	**********	**********	**********	**********	**********	**********	***90003**	******
11638000	37.0058	ALLENS RANCH	40.53. 0	109. 8. 0	5486.0	1962-1965	1963-1965	**********	**********	**********	**********	**********	**********	**********	**********	**9000
11640000	37.2864	FLAMING GORGE	40.56. 0	109.25. 0	6270.0	1958-1965	1959-1965	**********	**********	**********	**********	**********	**********	**********	********30	000000
11642000	37.0000	GREEN RIVER RS	40.53. 0	109.29. 0	6900.0	1916-1916	1916-1916	**********	**********	**********	******6***	**********	**********	**********	**********	******
11648000	37.0000	LINWOOD	41. 0. 0	109.39. 0	6000.0	1941-1942	1942-1942	**********	**********	**********	**********	**********	**********	*3********	**********	******
11648001	37.5377	MANILA	41. 0. 0	109.43. 0	6420.0	1910-1965	1955-1965	**********	**********	**********	7000000000	0000000000	0210000000	0**7***2**	**91000000	000000
11648600	37.0000	HOLE IN THE ROCK	40.57. 0	110.10. 0	8600.0	1916-1930	1930-1930	**********	**********	**********	******9000	5000035876	**********	**********	**********	******
11654050	42.1736	CHURCH BUTTES GA	41.26. 0	110. 2. 0	7045.0	1955-1965	1957-1965	**********	**********	**********	**********	**********	**********	**********	******2000	000000
11654200	42.0000	OPAL	41.46. 0	110.19. 0	6881.0	1916-1921	1921-1921	**********	**********	**********	******889*	3*********	**********	**********	**********	******
11654250	42.5105	KEMMERER	41.48. 0	110.32. 0	6954.0	1933-1965	1934-1965	**********	**********	**********	**********	**********	***8000000	0000000000	0000000000	000000
11654400	42.3430	FORT BRIDGER AIR	41.24. 0	110.25. 0	7016.0	1951-1965	1961-1965	**********	**********	**********	**********	**********	**********	**********	*30000****	500000
11654500	42.5836	LYMAN	41.20. 0	110.10. 0	6695.0	1922-1942	1933-1942	**********	**********	**********	**********	**40000501	4420000000	000*******	**********	******
11654800	42.0000	ROBERTSON	41. 9. 0	110.32. 0	7800.0	1943-1945	1945-1945	**********	**********	**********	**********	**********	**********	***301****	**********	******
11657000	42.7940	ROCK SPRINGS	41.35. 0	109.13. 0	6272.0	1952-1965	1952-1965	**********	**********	**********	**********	**********	**********	**********	**00050000	000000
11657001	42.7845	ROCK SPRINGS AIR	41.36. 0	109. 4. 0	6471.1	1954-1965	1955-1965	**********	**********	**********	**********	**********	**********	**********	****300000	000000
11657500	42.0000	SUPERIOR	41.46. 0	108.59. 0	7840.0	1914-1919	1919-1919	**********	**********	**********	*****20059	**********	**********	**********	**********	******
11657600	42.0000	BITTER CREEK 4NE	41.34. 0	108.34. 0	6702.0	1898-1945	1963-1965	**********	********95	20********	**********	**********	**********	**********	**********	**9000
11658000	42.4065	GREEN RIVER	41.32. 0	109.29. 0	6089.0	1897-1945	1952-1965	**********	*******97*	*****20000	2020000100	2000000000	0000000100	0000000002	2200000000	000000
11662100	42.3170	FARSON	42. 7. 0	109.26. 0	6591.0	1931-1965	1955-1965	**********	**********	**********	**********	**********	*000000000	00041*0400	2004100000	000000
11662810	42.0000	DUTCH JOE	42.37. 0	109.15. 0	7486.0	1916-1926	1926-1926	**********	**********	**********	*******636	6312678***	**********	**********	**********	******
11663000	42.3396	FONTENELLE DAM	41.59. 0	110. 4. 0	6470.0	1963-1965	1964-1965	**********	**********	**********	**********	**********	**********	**********	**********	***900
11666000	42.0000	FONTENELLE	42. 5. 0	110.15. 0	6700.0	1904-1908	1908-1908	**********	**********	****85966*	**********	**********	**********	**********	**********	******
11671000	42.5252	LA BARGE 4WNW	42.17. 0	110.15. 0	6830.0	1894-1965	1964-1965	**********	****67**9*	**********	**********	**********	**********	**********	**********	***800
11673000	42.0695	BIG PINEY	42.32. 0	110. 7. 0	6821.0	1938-1965	1939-1965	**********	**********	**********	**********	**********	********30	0000000000	0000000000	000000
11678120	42.0698	BIG SANDY	42.40. 0	109.30. 0	7200.0	1965-1965	1965-1965	**********	**********	**********	**********	**********	**********	**********	**********	*****9
11678450	42.7280	PINEDALE 1E	42.52. 0	109.51. 0	7210.0	1900-1965	1963-1965	**********	**********	******3004	1100500000	1414722000	0029*****3	0000000000	0700003350	004000
11678660	42.0000	WILLOW CREEK CAB	43. 5. 0	109.54. 0	7500.0	1906-1915	1915-1915	**********	**********	******9*31	*55126****	**********	**********	**********	**********	******
11678690	42.0000	CORA	42.57. 0	109.58. 0	7300.0	1942-1943	1943-1943	**********	**********	**********	**********	**********	**********	***9******	**********	******
11682000	42.0000	JENKINS RANCH	42.50. 0	110. 0. 0	7070.0	1940-1942	1941-1942	**********	**********	**********	**********	**********	**********	300*******	**********	******
11684000	42.0000	DANIEL	42.55. 0	110. 4. 0	6740.0	1899-1915	1915-1915	**********	*********3	0000000000	020040****	**********	**********	**********	**********	******
11684600	42.6165	MERNA	42.57. 0	110.22. 0	7780.0	1963-1965	1964-1965	**********	**********	**********	**********	**********	**********	**********	**********	****00
11690000	42.5115	KENDALL	43.12. 0	109.59. 0	7665.0	1904-1965	1952-1965	**********	**********	****3000**	*******312	5416099900	0000000000	0000000502	2100000000	000000
11700000	37.1168	CANYONLANDS-THE	38. 9. 0	109.45. 0	5040.0	1965-1965	1965-1965	**********	**********	**********	**********	**********	**********	**********	**********	*****9
11800000	37.1163	CANYONLANDS-THE	38.27. 0	109.50. 0	5900.0	1965-1965	1965-1965	**********	**********	**********	**********	**********	**********	**********	**********	*****3
11950000	37.4946	LA SAL	38.19. 0	109.15. 0	6075.0	1901-1965	1965-1965	**********	**********	*711514762	0502140412	2132335159	0000000143	500000005*	4930000000	05**43
12000001	37.0000	WARNER RS	38.31. 0	109.16. 0	9450.0	1916-1921	1921-1921	**********	**********	**********	******8999	99********	**********	**********	**********	******
12100000	37.5733	MOAB 4 NW	38.36. 0	109.36. 0	3965.0	1889-1965	1956-1965	*********9	0000000000	0000000000	0000000000	0000000000	0000000000	000000000*	0000240000	000000
12130000	37.0000	DALTON WELLS	38.43. 0	109.42. 0	4480.0	1941-1942	1942-1942	**********	**********	**********	**********	**********	**********	*38*******	**********	******
12150001	37.8705	THOMPSONS	38.58. 0	109.43. 0	5150.0	1911-1965	1952-1965	**********	**********	**********	*700731*76	0000000000	0000000000	0000000021	1100000000	000000
12300000	37.1230	CASTLETON	38.36. 0	109.19. 0	5920.0	1963-1965	1965-1965	**********	**********	**********	**********	**********	**********	**********	**********	****10
12700000	37.0000	FISHER VALLEY	38.40. 0	109. 5. 0	6000.0	1911-1911	1911-1911	**********	**********	**********	*9********	**********	**********	**********	**********	******
12708000	5.3246	GATEWAY 15W	38.40. 0	108.59. 0	4562.0	1947-1965	1948-1965	**********	**********	**********	**********	**********	**********	*******900	0000000000	000000
12708002	5.0000	WATERFALL RANCH	38.47. 0	108.41. 0	7500.0	1935-1942	1942-1942	**********	**********	**********	**********	**********	*****70000	00********	**********	******
12724000	5.8500	URAVAN	38.22. 0	108.44. 0	5013.0	1961-1965	1962-1965	**********	**********	**********	**********	**********	**********	**********	**********	*30000
12724150	5.0000	RED VALE	38.11. 0	108.24. 0	6350.0	1912-1922	1922-1922	**********	**********	**********	**80000500	003*******	**********	**********	**********	******
12724151	5.6012	NORWOOD	38. 8. 0	108.17. 0	7017.0	1931-1965	1951-1965	**********	**********	**********	**********	**********	*900000001	0130000000	1000000000	000000
12724152	5.0000	RED VALE (NEAR)	38. 3. 0	108.29. 0	6996.0	1939-1941	1941-1941	**********	**********	**********	**********	**********	*********9	10********	**********	******
12724450	5.6524	PLACERVILLE	38. 2. 0	108. 3. 0	7322.0	1947-1965	1956-1965	**********	**********	**********	**********	**********	**********	*******900	0010920000	000000
12724600	5.0000	ILIUM	37.55. 0	107.54. 0	8179.0	1915-1915	1915-1915	**********	**********	**********	*****7****	**********	**********	**********	**********	******
12724602	5.8454	TROUT LAKE	37.50. 0	107.53. 0	9700.0	1915-1956	1916-1956	**********	**********	**********	*****30000	0000000000	0000000000	0000000000	000000****	******
12732000	5.0000	RED ROCK	38.19. 0	108.53. 0	5380.0	1910-1911	1911-1911	**********	**********	**********	87********	**********	**********	**********	**********	******
12732001	5.6315	PARADOX	38.22. 0	108.58. 0	5309.0	1942-1965	1942-1965	**********	**********	**********	**********	**********	**********	**40000001	4000000000	000000
12748300	5.0000	LAVENDER	37.52. 0	108.29. 0	7091.0	1891-1894	1894-1894	**********	*0103*****	**********	**********	**********	**********	**********	**********	******
12784000	5.2326	DOLORES	37.28. 0	108.30. 0	6936.0	1909-1965	1944-1965	**********	**********	*********1	58****9000	000000000*	**********	*******900	0000000000	000000
12788000	5.7417	RICO	37.41. 0	108. 2. 0	8842.0	1891-1965	1911-1965	**********	*300000009	**********	1000000000	0000000000	0000000000	0000000000	0000000000	000000

Appendix A continued

CSU NO	BUREAU NO	NAME	LATITUDE	LONGITUDE	ELEVATION	RECORDING BEGAN-ENDED	CONTINUOUS RECORDING	188 0123456789	189 0123456789	190 0123456789	191 0123456789	192 0123456789	193 0123456789	194 0123456789	195 0123456789	196 012345
12900000	37,1440	CISCO	38,58, 0	109,19, 0	4330.0	1952-1965	1961-1965	**********	**********	**********	**********	**********	**********	**********	**90000001	200000
13000000	5,5041	LITTLE DOLORES 5	39, 3, 0	108,51, 0	6375.0	1961-1965	1963-1965	**********	**********	**********	**********	**********	**********	**********	**********	**8000
13000002	5,5040	LITTLE DOLORES	38,56, 0	108,51, 0	6700.0	1942-1955	1955-1955	**********	**********	**********	**********	**********	**********	**00000001	0****1****	******
13000003	5,0000	GLADE PARK	39, 0, 0	108,43, 0	6500.0	1911-1918	1912-1918	**********	**********	**********	*30000000*	**********	**********	**********	**********	******
13100000	37,3706	HARLEY DOME	39,10, 0	109, 8, 0	5247.0	1959-1963	1963-1963	**********	**********	**********	**********	**********	**********	**********	*********9	0003**
13500000	5,1772	COLORADO NATIONA	39, 6, 0	108,44, 0	5790.0	1940-1965	1951-1965	**********	**********	**********	**********	**********	**********	5000100000	1000000000	000000
13500001	5,3146	FRUITA 2 N	39,11, 0	108,44, 0	4510.0	1890-1965	1908-1965	**********	21000*****	***1000*00	0000000900	0000000000	0000000000	0000000000	0000000000	000000
13700000	5,0000	T.S.RANCH	39, 0, 0	108,19, 0	5250.0	1888-1901	1897-1901	*********5	3203101000	00********	**********	**********	**********	**********	**********	******
13709000	5,0000	ALTMAN	38,44, 0	108,10, 0	10640.0	1898-1898	1898-1898	**********	********6*	**********	**********	**********	**********	**********	**********	******
13715050	5,6081	OLATHE	38,37, 0	107,59, 0	5360.0	1941-1955	1955-1955	**********	**********	**********	**********	**********	**********	*600000000	000102****	******
13715051	5,5717	MONTROSE NO 1	38,29, 0	107,53, 0	5830.0	1939-1965	1944-1965	**********	**********	**********	**********	**********	*********6	2002000000	0000000000	000000
13715052	5,5722	MONTROSE NO 2	38,29, 0	107,53, 0	5830.0	1885-1965	1900-1965	*****30000	00009*0099	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000	000000
13715100	5,0000	FORT CRAWFORD	38,23, 0	107,49, 0	6605.0	1889-1890	1890-1890	*********7	3*********	**********	**********	**********	**********	**********	**********	******
13715150	5,0000	LUJANE	38,29, 0	107,44, 0	6620.0	1906-1910	1907-1910	**********	**********	******9000	0*********	**********	**********	**********	**********	******
13715600	5,6203	OURAY	38, 1, 0	107,41, 0	7720.0	1943-1965	1951-1965	**********	**********	**********	**********	**********	**********	***9000000	3000000000	000000
13715750	5,0000	IRONTON	37,56, 0	107,41, 0	9800.0	1909-1920	1920-1920	**********	**********	*********9	2000000000	3*********	**********	**********	**********	******
13716000	5,2192	DELTA 1 E	38,45, 0	108, 3, 0	5125.0	1888-1965	1889-1965	********30	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000	000000
13718100	5,1440	CEDAREDGE	39,54, 0	107,55, 0	6175.0	1891-1965	1947-1965	**********	*300000000	0000******	9100000053	0085000000	0000000000	0000001000	0000000000	000000
13730211	5,6306	PAONIA	38,52, 0	107,35, 0	5685.0	1957-1965	1958-1965	**********	**********	**********	**********	**********	**********	**********	*******800	000000
13730212	5,6307	PAONIA 1S	38,51, 0	107,34, 0	6125.0	1892-1957	1957-1957	**********	**6222100*	*****40000	0000000000	0000000000	0000000000	0001300000	00010005**	******
13730350	5,9845	WILCOX RANCH	38,55, 0	107,32, 0	5950.0	1948-1951	1949-1951	**********	**********	**********	**********	**********	**********	********30	0*********	******
13730700	5,0000	COLUMBINE RANCH	39, 2, 0	107,31, 0	6975.0	1909-1934	1911-1934	**********	**********	**********	1000000000	0000000000	00000*****	**********	**********	******
13730701	5,8963	WEST MUDDY RANGE	39, 6, 0	107,31, 0	8600.0	1956-1957	1957-1957	**********	**********	**********	**********	**********	**********	**********	86877877**	******
13730800	5,6651	POWDER HORN	39, 7, 0	107,38, 0	8600.0	1964-1965	1965-1965	**********	**********	**********	**********	**********	**********	**********	**********	****90
13733300	5,0000	CRAWFORD	38,42, 0	107,36, 0	6800.0	1909-1922	1910-1922	**********	**********	*********8	0000000000	000*******	**********	**********	**********	******
13736000	5,0000	RIVER PORTAL	38,31, 0	107,39, 0	6532.0	1906-1916	1911-1916	**********	**********	******9000	1000000***	**********	**********	**********	**********	******
13742250	5,1609	CIMARRON	38,24, 0	107,31, 0	7096.0	1951-1965	1965-1965	**********	**********	**********	**********	**********	**********	**********	*000000000	000041
13745000	5,7456	SAPINERO 9W	38,28, 0	107,28, 0	9300.0	1920-1946	1946-1946	**********	**********	**********	**********	3000000000	0000000000	0004678***	**********	******
13748000	5,0000	SAPINERO (NEAR)	38,27, 0	107,25, 0	8125.0	1899-1919	1906-1919	**********	*********9	000**70000	0000000000	**********	**********	**********	**********	******
13754000	5,6966	RED STONE	39,11, 0	107,14, 0	7200.0	1963-1964	1964-1964	**********	**********	**********	**********	**********	**********	**********	**********	***91*
13754001	5,4734	LAKE CITY	38, 3, 0	107,19, 0	8690.0	1905-1965	1948-1965	**********	**********	*****70000	0000029***	**********	**********	*******900	0000000000	000000
13760250	5,0000	CATHEDRAL	38, 4, 0	107, 3, 0	8925.0	1917-1934	1934-1934	**********	**********	**********	********20	0300021100	00001*****	**********	**********	******
13763000	5,7455	SAPINERO 8E	38,28, 0	107,10, 0	7800.0	1960-1965	1961-1965	**********	**********	**********	**********	**********	**********	**********	**********	*00000
13772000	5,1713	COCHETOPA CR	38,26, 0	106,46, 0	8000.0	1909-1965	1949-1965	**********	**********	*********8	0000009***	**********	**********	********10	0000000000	000000
13772400	5,6513	PITKIN	38,36, 0	106,32, 0	9200.0	1909-1965	1946-1965	**********	**********	*********8	0000000000	0000000000	0000000000	0000030000	0000000000	000000
13772700	5,7461	SARGENTS 6W	38,24, 0	106,28, 0	8125.0	1899-1958	1958-1958	**********	*********9	1*********	**********	**********	**********	*******900	000000002*	******
13772701	5,7460	SARGENTS	38,24, 0	106,28, 0	8465.0	1958-1965	1959-1965	**********	**********	**********	**********	**********	**********	**********	********90	000000
13775000	5,3662	GUNNISON	38,33, 0	106,58, 0	7694.0	1888-1965	1963-1965	********90	4**9000040	1300000000	0000000000	0000000000	0002300000	0000000000	0000000000	021000
13781450	5,1959	CRESTED BUTTE	38,52, 0	106,58, 0	8855.0	1910-1965	1953-1965	**********	**********	**********	1000000004	0000000000	0000000000	0000000000	0010000000	000000
13790000	5,8184	TAYLOR PARK	38,49, 0	106,37, 0	9206.0	1941-1965	1942-1965	**********	**********	**********	**********	**********	**********	*100000000	0000000000	000000
13800001	5,3489	GRAND JUNCTION 6	39, 3, 0	108,27, 0	4710.0	1962-1965	1964-1965	**********	**********	**********	**********	**********	**********	**********	**********	**6700
13800003	5,3488	GRAND JUNCTION 4	39, 7, 0	108,32, 0	4849.0	1885-1965	1952-1965	*****9*75*	**30000000	0000000000	0000000000	0000000000	09********	**********	**00000000	000000
14000000	5,6266	PALISADE 1 S	39, 6, 0	108,21, 0	4740.0	1911-1965	1951-1965	**********	**********	**********	*710000000	8700000000	0023000000	0000000000	1000000000	000000
14280000	5,0825	BONHAM RESERVOIR	39, 6, 0	107,54, 0	9870.0	1963-1965	1965-1965	**********	**********	**********	**********	**********	**********	**********	**********	***910
14290000	5,1741	COLLBRAN	39,14, 0	107,58, 0	6137.0	1892-1965	1952-1965	**********	**30000000	0000000000	0000000000	2300000000	0000000000	0000000002	0100000000	000003
14300000	5,0000	DEBEQUE	38,19, 0	108,12, 0	4935.0	1910-1954	1954-1954	**********	**********	**********	665*******	**********	**********	**********	**203*****	******
14520000	5,0714	ALTENBERN	39,30, 0	108,23, 0	5690.0	1947-1965	1948-1965	**********	**********	**********	**********	**********	**********	*******900	0000000000	000000
14700000	5,0000	GRAND VALLEY	39,28, 0	108, 2, 0	5100.0	1889-1913	1890-1913	*********9	0000000000	0000000000	0000******	**********	**********	**********	**********	******
14760000	5,6673	OIL SHALE MINE	39,33, 0	107,56, 0	8200.0	1947-1951	1948-1951	**********	**********	**********	**********	**********	**********	*******400	00********	******
14900000	5,7031	RIFLE 2 ENE	39,33, 0	107,44, 0	5319.0	1911-1965	1933-1965	**********	**********	**********	*800000000	00000*09*8	3010000000	0000000000	0000000000	000000
15150000	5,0000	RIFLE FALLS	39,41, 0	107,42, 0	5618.0	1889-1891	1891-1891	*********7	89********	**********	**********	**********	**********	**********	**********	******
15200000	5,0000	SILT	39,33, 0	107,39, 0	5441.0	1900-1907	1907-1907	**********	**********	30010901**	**********	**********	**********	**********	**********	******
15545000	5,0000	LONESOME	39,18, 0	107,32, 0	7500.0	1917-1918	1918-1918	**********	**********	**********	*******68*	**********	**********	**********	**********	******
15921000	5,0000	MARBLE	39, 4, 0	107,10, 0	7951.0	1909-1917	1917-1917	**********	**********	*********3	00000006**	**********	**********	**********	**********	******
15924000	5,0000	EMMA	39,22, 0	107, 3, 0	-.1	1889-1891	1891-1891	**********	90********	**********	**********	**********	**********	**********	**********	******
15942000	5,0514	BASALT	39,22, 0	107, 2, 0	6624.0	1965-1965	1965-1965	**********	**********	**********	**********	**********	**********	**********	**********	*****2
15942120	5,5507	MEREDITH	39,22, 0	106,45, 0	7797.0	1963-1965	1964-1965	**********	**********	**********	**********	**********	**********	**********	**********	***900
15942140	5,5513	MEREDITH 4NE	39,22, 0	106,41, 0	8500.0	1949-1953	1953-1953	**********	**********	**********	**********	**********	**********	**********	2103******	******
15942600	5,0000	NAST	39,18, 0	106,37, 0	8880.0	1909-1934	1934-1934	**********	**********	*********3	0000000000	*000900000	84001*****	**********	**********	******
15943000	5,0370	ASPEN	39,11, 0	106,50, 0	7913.0	1888-1965	1951-1965	********75	939******5	6*********	****300003	**********	****000000	0000000000	1000000000	000000
15970000	5,0000	ASHCROFT	39, 4, 0	106,48, 0	9483.0	1901-1922	1914-1922	**********	**********	*300000000	0005100800	000*******	**********	**********	**********	******
15984000	5,4270	INDEPENDENCE PAS	39, 5, 0	106,39, 0	10550.0	1947-1958	1951-1958	**********	**********	**********	**********	**********	**********	*******900	100000400*	******
16100000	5,3359	GLENWOOD SPRINGS	39,34, 0	107,20, 0	5823.0	1888-1965	1954-1965	********70	8**91****9	4810000004	0000140008	0000050000	0000000000	0000000000	4001000000	000000
16300000	5,7618	SHOSHONE	39,34, 0	107,14, 0	5923.0	1910-1965	1911-1965	**********	**********	**********	3000000000	0000000000	0000000000	0000000000	0000000000	000000
16614001	5,2454	EAGLE FAA AIRPOR	39,39, 0	106,55, 0	6497.0	1904-1965	1944-1965	**********	**********	****900000	08********	**********	**********	**71000000	0000000000	000000
16620000	5,0000	EAGLE	39,39, 0	106,50, 0	6598.0	1904-1947	1944-1947	**********	**********	****900011	2*********	**********	**********	**710000**	**********	******
16620001	5,0000	PINEY	39,42, 0	106,32, 0	8000.0	1917-1919	1919-1919	**********	**********	**********	*******8*3	**********	**********	**********	**********	******
16620002	5,0000	AVON	39,37, 0	106,29, 0	7445.0	1938-1942	1942-1942	**********	**********	**********	**********	**********	********30	036*******	**********	******
16670000	5,6917	REDCLIFF	39,31, 0	106,22, 0	8608.0	1890-1951	1951-1951	**********	530101110*	**********	1010110***	**********	**********	********07	11********	******
17100000	5,0810	BOND	39,53, 0	106,42, 0	6700.0	1958-1965	1960-1965	**********	**********	**********	**********	**********	**********	**********	*********2	000000
17300000	5,0000	BLUE VALLEY RANC	39,59, 0	106,23, 0	7400.0	1907-1916	1916-1916	**********	**********	********00	1**8017***	**********	**********	**********	**********	******
17403000	5,3592	GREEN MOUNTAIN D	39,53, 0	106,20, 0	7740.0	1939-1965	1952-1965	**********	**********	**********	**********	**********	*********0	0000000000	0100000000	000000
17445000	5,2281	DILLON 1 S	39,36, 0	106, 3, 0	8960.0	1891-1965	1914-1965	**********	*306******	*********8	5033000000	0000000000	0000000000	0000000000	0000000000	000000
17448600	5,1660	CLIMAX 2 NW	39,23, 0	106,12, 0	11300.0	1952-1965	1953-1965	**********	**********	**********	**********	**********	**********	**********	**1000*000	000000
17480000	5,0909	BRECKENRIDGE	39,29, 0	106, 2, 0	9579.0	1889-1965	1948-1965	*********3	0000000000	0000000000	0005******	**********	**********	*******900	0000000000	000000

Appendix A continued

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CSU NO    BUREAU NO NAME              LATITUDE  LONGITUDE  ELEVATION RECORDING  CONTINUOUS  1          1          1          1          1          1          1          1          1      1
                                                                     BEGAN-ENDED RECORDING   8          8          9          9          9          9          9          9          9      9
                                                                                             8          9          0          1          2          3          4          5          6      6
                                                                                             0123456789 0123456789 0123456789 0123456789 0123456789 0123456789 0123456789 0123456789 012345

17520000  5.4664  KREMMLING         40. 4. 0  106.24. 0  7359.0   1908-1965  1965-1965   ********** ********** ********30 1********* ********** ********** *****80085 1106****** ****70
17540000  5.3423  GORE PASS RANCH   40. 9. 0  106.28. 0  7682.0   1957-1963  1958-1963   ********** ********** ********** ********** ********** ********** ********** *******000 0000**
17710000  5.0000  PARSHALL          40. 1. 0  106.15. 0  7765.0   1909-1912  1912-1912   ********** ********** *********3 130******* ********** ********** ********** ********** ******
17720002  5.6342  PARSHALL 10SSE    39.55. 0  106. 7. 0  8270.0   1951-1965  1957-1965   ********** ********** ********** ********** ********** ********** ********** *400187000 000000
17740000  5.0000  LEAL              39.49. 0  106. 3. 0  8600.0   1910-1910  1910-1910   ********** ********** ********** 5********* ********** ********** ********** ********** ******
17740001  5.3345  GLEN HAD          39.47. 0  106. 1. 0  8687.0   1947-1951  1951-1951   ********** ********** ********** ********** ********** ********** *******963 1********* ******
17900000  5.4129  HOT SULPHUR SPRI  40. 3. 0  106. 4. 0  7680.0   1896-1965  1955-1965   ********** ******13** ********** ********** ********** ********** **300***** ***7100000 000000
18026000  5.3113  FRASER            39.57. 0  105.50. 0  8560.0   1889-1965  1930-1965   *********5 5********* ********** 2000000000 0000000004 0000000000 0000000000 0000000000 000000
18034000  5.9175  WINTER PARK       39.54. 0  105.46. 0  9058.0   1943-1965  1950-1965   ********** ********** ********** ********** ********** ********** ***1000001 0000000000 000000
18081000  5.0674  BERTHOUD PASS     39.49. 0  105.47. 0 11314.0   1950-1965  1964-1965   ********** ********** ********** ********** ********** ********** ********** 8********* ***900
18500000  5.3500  GRAND LAKE 6 SSW  40.11. 0  105.52. 0  8280.0   1952-1965  1952-1965   ********** ********** ********** ********** ********** ********** ********** **00000000 000000
18500001  5.3508  GRAND VALLEY      40.11. 0  105.52. 0  8268.0   1965-1965  1965-1965   ********** ********** ********** ********** ********** ********** ********** ********** *****7
19500000  5.3496  GRAND LAKE 1 NW   40.14. 0  105.50. 0  8576.0   1907-1965  1947-1965   ********** ********** *******051 0000000000 04******** ********** 0001318000 0000000000 000000
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APPENDIX B

Table of mean spring runoff, of mean winter precipitation, of correlation coefficient between winter, spring precipitation and spring runoff, of expected increase in spring runoff, and of the number of years needed for evaluation, based on the two-sample u-test.

Column 1 of Table B lists the CSU code number for identification of runoff station (7 digits) or precipitation station (8 digits).

Column 2 of Table B lists the mean spring runoff or the mean winter precipitation, in inches.

Column 3 lists the variance of the spring runoff, in inches square .

Column 4 lists the coefficient of correlation between spring runoff and precipitation from one or several precipitation gages.

Column 5 indicates the number of years of record on which the correlation is based.

Column 6 gives the value of coefficient b_j of equation (11) for each precipitation station.

Column 7 gives the expected value of increase in spring runoff (inches) corresponding to a 10% increase in winter precipitation at each precipitation station.

Column 8 gives the expected relative increase in spring runoff assuming a uniform 10% increase in winter precipitation.

Column 9 gives the number of years for evaluation at the 95% level of significance and 50% power assuming a uniform 10% increase in winter precipitation.

TABLE

Column 1	2	3	4	5	6	7	8	9
CSU ID	Mean in.	Variance in.^{2}	Cor Cof	Case	Coeff	Increase Runoff	Increase Ratio	Years Eval.
1071830	.50	.08	.96	13		.040	.080	192
10718302	8.87				.045			
1071860	1.29	.23	.98	14		.087	.067	117
10718600	8.02				.108			
1073020	.68	.55	.93	10		.155	.228	87
10730600	7.95				.444			
10730603	10.42				-.190			
1073040	1.02	.63	.95	10		.184	.180	71
10730600	7.95				.479			
10730603	10.42				-.189			
1073060	1.49	1.44	.94	10		.316	.212	55
10730600	7.95				.867			
10730603	10.42				-.358			
1073200	3.38	2.98	.98	52		.383	.113	77
10734000	4.42				-.324			
10734040	5.10				-.038			
10734360	11.06				.220			
10734641	18.60				.048			
10734680	12.90				.046			
10738000	4.27				-.084			
10758200	8.52				.075			
10770000	9.37				.136			
1073400	6.74	9.71	.98	52		.694	.103	77
10734000	4.42				0			
10734040	5.10				-.343			
10734360	11.06				.443			
10734641	18.60				.120			
10734680	12.90				.121			
1073408	8.12	12.78	.98	31		.830	.102	71
10734360	11.06				.280			
10734641	18.60				.221			
10734680	12.90				.085			
1073436	38.89	7.74	.98	52		1.117	.029	23
10734360	11.06				.480			
10734641	18.60				.286			
10734680	12.90				.042			
1073448	8.91	22.00	.97	9		.726	.082	160
10734560	11.65				1.287			
10734561	15.04				-.514			
1073460	15.98	34.29	.99	11		1.415	.089	65
10734641	18.60				.761			
10734680	12.90				0.0			

Table continued

1 CSU ID	2 Mean	3 Variance	4 Cor Cof	5 Case	6 Coeff	7 Increase Runoff	8 Increase Ratio	9 Years Eval.
1074400	3.87	4.24	.97	25		.399	.103	102
10750001	6.51				.377			
10758200	8.52				-.261			
10758400	15.47				-.085			
10764201	11.03				0.0			
10770000	9.37				.311			
10774000	11.90				-.120			
10776001	13.78				.081			
10778600	30.53				.081			
1075200	3.16	3.33	.99	15		.372	.118	92
10758200	8.52				-.464			
10758400	15.47				-.874			
10764201	11.03				0.			
10770000	9.37				1.551			
10774000	11.90				-.223			
10776001	13.78				.698			
10778600	30.53				-.010			
1075820	7.40	19.69	.89	19		.441	.060	389
10758200	8.52				0			
10758400	15.47				.285			
1076200	6.12	8.21	.97	22		.587	.096	91
10764201	11.03				.076			
10770000	9.37				.365			
10774000	11.90				-.314			
10776001	13.78				.388			
1076800	5 64	9.80	.98	25		.749	.133	67
10770000	9.37				.460			
10774000	11.90				-.314			
10776001	13.78				.502			
10778600	30.53				0.			
1077200	9.43	29.10	.97	13		1.019	.108	107
10774000	11.90				.856			
1077600	16.05	72.85	.97	17		1.479	.092	128
10776001	13.78				1.073			
1077800	19.70	74.85	.97	25		1.652	.084	105
10778600	30.53				.541			
1146300	.51	.03	.97	21		.045	.089	55
11463000	3.44				.132			
1160121	1.31	1.87	.84	17		.162	.123	274
11601300	4.22				-.127			
11601420	4.29				.502			
1160720	2.41	1.74	.98	29		.187	.078	191
11607400	9.38				-.012			
11607601	15.72				.126			
1160725	2.71	2.83	.96	30		.351	.130	88
11607400	9.38				-.125			
11607601	15.72				.298			
1160740	4.22	9.30	.83	25		.225	.053	704
11607400	9.38				.240			
1160755	4.49	5.66	.95	25		.489	.109	90
11607601	15.72				.311			
1161500	1.40	.29	.98	25		.190	.136	30
11615004	5.47				.083			
11615150	7.35				.097			
11615202	8.94				.067			
11615550	12.25				.011			
1161520	4.93	2.58	.98	16		.380	.077	68
11615202	8.94				.240			
11615550	12.25				.135			
1161525	6.99	4.00	.98	17		.592	.085	43
11615550	12.25				.483			
1161706	.47	.09	.90	13		.032	.067	347
11617060	4.78				.066			
1161725	2.19	1.33	.99	10		.259	.118	76
11617250	3.24				0.			
11617270	4.20				-.897			
11617350	9.95				.210			
11617460	4.58				.932			
11617850	6.02				0.			

Table continued

1	2	3	4	5	6	7	8	9
CSU ID	Mean	Variance	Cor Cof	Case	Coeff	Increase Runoff	Increase Ratio	Years Eval.
1161726	2.66	3.42	.97	25		.163	.061	492
11617270	4.20				.280			
11617350	9.95				.046			
1161746	2.31	1.65	.95	15		.207	.090	148
11617530	6.67				.406			
11617631	7.11				-.090			
1161752	1.52	1.08	.93	15		.205	.135	98
11617530	6.67				.308			
1161774	5.10	4.07	.99	12		.370	.072	114
11617580	6.02				.614			
1161783	5.30	4.25	.99	12		.400	.076	101
11617850	6.02				.665			
1161785	7.95	7.49	.99	11		.709	.089	57
11617850	6.02				1.170			
1162200	1.13	.84	.96	12		.066	.059	737
11622001	4.76				.139			
1163200	1.75	.52	.98	20		.147	.084	92
11632080	6.91				.213			
1163203	1.82	.86	.96	15		.190	.104	91
11632080	6.91				.275			
1163243	5.25	2.99	.99	25		.114	.022	880
11632490	10.11				-.197			
11632570	7.31				-.192			
11632610	9.20				.322			
11632690	12.12				.165			
11632850	15.17				-.028			
11632940	9.19				0.			
1163256	7.70	3.09	.99	25		.555	.072	38
11632570	7.31				.257			
11632610	9.20				.047			
11632690	12.12				-.087			
11632850	15.17				.283			
11632940	9.19				0.			
1163257	1.99	.87	.97	21		.156	.079	136
11632570	7.31				.214			
1163268	3.83	4.62	.94	9		.288	.075	213
11632690	12.12				.238			
1163274	16.58	17.40	.97	18		1.331	.080	37
11632801	14.71				.900			
1163280	19.34	29.98	.96	32		1.399	.072	58
11632801	14.71				.951			
1163285	8.64	6.40	.98	18		.562	.065	77
11632940	9.19				.612			
1163291	2.78	1.48	.97	25		.145	.052	269
11632940	9.19				.158			
1164700	1.19	.17	.98	15		.066	.056	149
11648001	5.13				.019			
11654500	5.50				.050			
11658000	4.00				.036			
11662180	3.78				.048			
11678450	5.29				-.070			
11690000	9.79				.034			
1165000	1.30	.28	.98	34		.099	.076	109
11654250	4.96				.167			
11658000	4.00				.062			
11662180	3.78				-.082			
11673000	3.85				-.167			
11678450	5.29				.038			
11690000	9.79				.068			
1165400	.88	.28	.96	17		.081	.092	165
11654050	4.08				.046			
11654250	4.96				-.075			
11654400	4.31				.230			
1165410	1.01	.28	.94	15		.052	.051	404
11654250	4.96				.104			
1165445	1.74	.97	.92	5		.113	.065	293
11654500	5.50				.205			
1166200	.15	.01	.93	10		.007	.048	744
11662180	3.78				.019			

Table continued

1	2	3	4	5	6	7	8	9
CSU ID	Mean	Variance	Cor Cof	Case	Coeff	Increase Runoff	Increase Ratio	Years Eval.
1167800	5.51	3.45	.80	15		.397	.072	83
11678450	5.29				.751			
1167827	6.93	5.27	.95	50		.398	.057	127
11678450	5.29				.753			
1167845	11.91	17.94	.93	40		.668	.056	154
11678450	5.29				1.260			
1167857	2.54	.69	.97	6		.196	.077	69
11678690	5.57				.351			
1168800	10.63	5.67	.98	33		.663	.062	49
11690000	9.79				.677			
1270000	1.58	1.03	.96	25		.217	.138	83
12708000	6.54				.067			
12724151	8.45				-.047			
12724450	7.30				-.012			
12724602	16.59				.109			
12732001	6.09				-.109			
12764000	11.25				.367			
12788000	15.33				-.203			
1272400	2.10	2.85	.96	24		.525	.157	39
12724151	8.45				.481			
12724450	7.30				-.096			
12724601	16.59				.114			
1272430	3.77	4.80	.95	13		.471	.125	83
12724450	7.30				.347			
12724602	16.59				.131			
1272445	7.39	7.76	.91	22		.539	.073	102
12724450	7.30				.739			
1272455	7.66	12.54	.96	18		.816	.107	72
12724602	16.59				.492			
1274000	3.07	.95	.97	13		.344	.112	30
12764000	11.25				.186			
12788000	15.33				.088			
1275600	5.43	10.64	.94	26		.606	.112	111
12764000	11.25				.490			
12788000	15.33				.036			
1277200	8.78	14.37	.96	43		.805	.092	85
12788000	15.33				.520			
1278000	8.80	15.99	.97	25		.958	.109	66
12788000	15.33				.625			
1371200	4.24	3.84	.98	16		.561	.132	46
13730212	9.62				.159			
13772400	8.71				.286			
13775000	5.18				-.234			
13781450	14.25				-.188			
13790000	9.10				.602			
1371505	3.51	1.85	.98	25		.346	.099	59
13715051	5.26				1.209			
13715052	5.15				-.989			
13715600	11.69				.188			
1371510	3.93	.39	.99	8		.412	.105	8
13715150	6.44				.630			
1371515	5.79	1.48	.99	8		.743	.128	10
13715150	6.44				1.150			
1371520	5.96	4.60	.97	22		.228	.038	341
13715600	5.15				.442			
1371565	24.61	8.79	.98	11		2.327	.095	6
13715750	13.49				1.720			
1371810	7.58	11.42	.96	48		.610	.081	117
13718100	6.70				.911			
1373000	7.35	14.92	.97	15		.457	.062	274
13730211	8.71				-.382			
13730212	9.69				.821			
1373035	10.04	5.69	.99	9		.963	.096	23
13730700	14.70				.655			
1373055	9.60	12.60	.95	15		.513	.053	184
13730701	12.12				.423			
1373070	8.23	25.00	.93	8		.698	.085	197
13730701	12.12				.567			

Table continued

1	2	3	4	5	6	7	8	9
CSU ID	Mean	Variance	Cor Cof	Case	Coeff	Increase Runoff	Increase Ratio	Years Eval.
1374500	3.72	4.09	.97	25		.502	.135	62
13754001	8.05				.329			
13772000	4.97				.484			
13742400	8.71				.118			
13772700	6.12				-.634			
13775000	5.18				-.590			
13781450	14.25				.071			
13790000	9.10				.534			
1375100	3.66	1.40	.98	25		.173	.047	179
13754001	8.05				-.161			
13772000	4.97				.326			
13772400	8.71				-.030			
13772700	6.12				-.040			
13775000	5.18				-.239			
13781450	14.25				.014			
13790000	9.10				.327			
1375400	7.47	6.62	.97	17		.621	.083	65
13754001	8.05				.772			
1376300	3.29	2.19	.97	27		.347	.106	69
13772000	4.97				.436			
13772400	8.71				-.101			
13775000	5.18				-.203			
13781450	14.25				.065			
13790000	9.10				.254			
1377200	1.47	.73	.93	27		.125	.085	180
13772000	4.97				.188			
13772400	8.71				.036			
1377230	4.58	5.35	.94	27		.358	.078	160
13772400	8.71				.411			
1377500	7.78	7.85	.98	20		.658	.085	69
13775000	5.18				-.225			
13781450	14.25				.229			
13790000	9.10				.493			
1378100	12.60	15.53	.97	30		.798	.063	93
13781450	14.25				.56			
1378145	23.66	9.67	.96	11		1.540	.065	15
13781450	14.25				1.084			
1378400	5.95	5.91	.97			.510	.086	87
13790000	9.10				.560			
1420000	3.10	3.15	.94	25		.386	.124	81
14250000	9.69				.398			
1590000	9.54	9.31	.97	18		.696	.073	73
15963000	11.30				.616			
1592110	16.99	24.24	.99	8		.675	.040	204
15921800	17.12				.394			
1592140	17.13	18.43	.98	14		1.169	.068	51
15921800	17.12				.683			
1592160	18.71	39.28	.98	9		.909	.049	182
15921800	17.12				.531			
1592170	20.02	27.48	.99	5		1.765	.088	33
15921800	17.12				1.031			
1592180	35.09	47.91	.99	7		1.063	.030	162
15921800	17.12				.621			
1594212	16.78	16.83	.98	10		1.602	.095	25
15942180	12.20				1.313			
1594218	9.47	12.99	.99	6		.785	.080	86
15942180	12.20				.621			
1596300	18.94	22.29	.99	5		1.425	.075	42
15963000	11.30				1.260			
1598400	15.36	16.22	.98	12		1.003	.065	61
15984000	17.41				.576			
1600000	6.37	3.60	.99	25		.339	.053	120
16100000	9.47				-.158			
16300000	10.80				-.541			
16614001	6.14				.442			
17403000	8.56				-.112			
17448600	14.32				.038			
17460000	12.34				-.444			
17720002	9.71				.023			

Table continued

1	2	3	4	5	6	7	8	9
CSU ID	Mean	Variance	Cor Cof	Case	Coeff	Increase Runoff	Increase Ratio	Years Eval.
17900000	7.08				1.029			
18036000	10.69				-.349			
18054000	15.82				-.135			
18500000	6.80				.745			
19500000	9.76				.738			
1650000	5.59	3.08	.96	24		.326	.058	111
17403000	8.56				0.			
17448600	14.32				.075			
17460000	12.34				-.304			
17720002	9.71				0.			
17900000	7.08				.178			
18036000	10.69				-.101			
18054000	15.82				-.043			
18500000	6.80				.427			
19500000	9.76				.362			
1700000	5.98	7.32	.96	25		.467	.078	129
17403000	8.56				-.061			
17460000	12.34				-.217			
18036000	10.69				.311			
18054000	15.82				.128			
19500000	9.76				.258			
1740000	8.15	4.67	.98	17		.824	.101	26
17403000	8.56				.120			
17448600	14.32				.278			
17460000	12.34				.262			
1742100	8.29	6.21	.98	21		.784	.095	38
17448600	14.32				.338			
17460000	12.34				.243			
1743900	8.64	9.13	.98	15		1.034	.120	32
17448600	14.32				.268			
17460000	12.34				.527			
1744800	11.85	11.24	.98	8		.965	.081	46
17448600	14.32				.674			
1744815	9.80	9.68	.99	7		1.403	.143	18
17448600	14.32				.980			
1745400	8.90	5.95	.98	14		.856	.096	31
17460000	12.34				.694			
1745700	6.82	5.02	.98	7		1.514	.222	8
17460000	12.34				1.220			
1770000	5.57	6.33	.95	16		.326	.059	228
17720002	9.71				.336			
1790000	9.03	7.63	.98	25		.655	.073	68
18036000	10.69				.332			
18054000	15.82				-.201			
18500000	6.80				.585			
19500000	9.76				.226			
1800000	7.26	5.21	.98	18		.738	.102	36
18036000	10.69				.374			
18054000	15.82				.214			
1801800	19.00	19.60	.98	21		1.381	.073	39
18036000	10.69				1.292			
1801816	3.98	22.89	.90	30		.649	.163	208
18036000	10.69				.607			
1820000	11.58	9.96	.97	20		.932	.080	44
19500000	9.76				.955			
1830000	13.88	16.54	.99	14		.978	.078	53
18500000	6.80				.161			
19500000	9.76				1.002			
1890000	14.48	11.46	.993	12		.956	.066	48
19500000	9.76				.980			
1920000	18.83	21.18	.99	8		1.567	.083	33
19500000	9.76				1.606			
1930000	16.89	23.05	.99	8		1.363	.081	47
19500000	9.76				1.390			
1960000	12.28	18.66	.97	31		.923	.075	84
19500000	9.76				.946			
1073080	13.50	38.37	.97	14		1.146	.085	112
10734560	11.65				.984			
1073420	12.21	34.79	.98	5		1.004	.082	132
10734560	11.65				.862			

Table continued

1 CSU ID	2 Mean	3 Variance	4 Cor Cof	5 Case	6 Coeff	7 Increase Runoff	8 Increase Ratio	9 Years Eval.
1073448	8.91	22.00	.96	19		.984	.110	87
10734560	11.65				.565			
10734641	18.60				.175			
1073460	15.91	36.36	.99	11		1.495	.094	62
10734641	18.60				.804			
1075830	12.47	26.43	.97	22		1.010	.081	99
10758400	15.47				.653			
1076420	9.02	25.30	.97	22		.878	.097	126
10758400	15.47				.290			
10774000	11.90				-.081			
10778600	30.56				.172			
1077015	9.37	17.80	.97	25		.939	.100	77
10774000	11.90				.571			
10778600	30.53				.085			
1077200	8.64	24.35	.97	13		1.019	.118	90
10774000	11.90				.856			
1077250	15.39	47.06	.97	25		1.305	.085	106
10774000	11.90				1.097			
1077400	13.66	40.00	.98	25		1.460	.107	72
10774000	11.90				-.142			
10776001	13.78				.699			
10778600	30.53				.218			
1272440	5.46	27.64	.91	15		1.142	.209	81
12724602	15.69				.728			
1272445	7.39	7.76	.98	9		.555	.075	96
12724450	7.30				.189			
12724602	15.69				.266			
1278800	13.57	39.08	.96	13		1.571	.116	60
12788000	15.33				1.025			
1371530	2.94	2.41	.93	9		.234	.079	169
12724450	7.30				-.117			
13715600	11.69				.273			
1371555	9.19	2.93	.99	6		1.158	.126	8
13715600	11.69				.991			
1762500	4.04	3.84	.96	11		.310	.077	153
18036000	10.69				.125			
18054000	18.52				.095			
1800900	5.71	4.13	.94	10		.509	.089	61
18036000	10.69				.476			
1801800	19.00	19.60	.98	21		1.381	.073	39
18036000	10.69				1.292			
1801816	8.98	22.89	.90	30		.649	.072	208
18036000	10.69				.607			
1802730	9.27	12.31	.94	31		.662	.071	108
18036000	10.69				.619			
1804500	5.05	18.41	.81	31		.753	.149	124
18054000	15.82				.476			
1805400	10.99	44.69	.86	22		.261	.024	2019
18054000	15.82				.165			
1810000	2.72	9.10	.78	11		.549	.202	115
18500000	6.80				.808			
1850000	6.42	8.22	.99	5		.854	.133	43
19500000	9.76				.875			
1866000	19.94	20.23	.99	18		1.528	.077	33
19500000	9.76				1.566			
1880000	10.36	16.47	.99	5		.949	.092	70
18500000	6.80				1.395			
1920000	18.83	21.18	.99	8		1.566	.083	33
19500000	9.76				1.605			
1930000	16.89	23.05	.99	8		1.363	.081	47
19500000	9.76				1.397			
1960000	12.28	18.66	.97	18		.923	.075	84
19500000	9.76				.946			

Table continued

1	2	3	4	5	6	7	8	9
CSU ID	Mean	Variance	Cor. Coef	Case	Coeff	Increase Runoff	Increase Ratio	Years Eval.
1072030	7.10	15.86	.91	14		.81	.114	92
10724000	3.94				2.05			
1072045	7.09	20.67	.97	14		.69	.098	164
10724000	3.94				1.76			
1072060	11.36	31.71	.99	14		1.07	.094	105
10724000	3.94				2.72			
1073412	2.94	2.96	.95	15		.290	.099	134
10734360	11.06				.26			
1076400	8.98	7.97	.97	15		.840	.094	43
10770000	9.37				.89			
1082075	6.70	3.67	.94	14		.510	.076	54
10810001	6.15				.82			
1086000	.69	.13	.95	10		.062	.089	132
10810001	6.15				.10			
1148100	1.73	.16	.95	9		.121	.070	41
11463000	3.44				.35			
1160133	4.90	4.13	.95	17		.368	.075	117
11601420	4.29				.85			
1160142	2.36	4.44	.89	11		.242	.102	292
11601420	4.29				.56			
1160145	5.42	5.12	.95	32		.379	.070	137
11601420	4.29				.88			
1160181	1.88	.914	.914	12		.072	.072	428
11601420	4.29				.16			
1160184	5.11	4.77	.94	55		.367	.072	136
11601420	4.29				.85			
1160190	22.97	22.40	.97	10		1.716	.075	29
11601420	4.29				4.00			
1160765	8.37	13.50	.95	26		.691	.083	108
11607150	5.19				1.33			
1160770	12.98	33.18	.96	24		1.090	.085	105
11607150	5.19				2.10			
1161250	.41	.07	.91	14		.056	.137	84
11615004	5.47				.10			
1161530	2.41	1.44	.95	15		.227	.094	107
11615550	12.25				.18			
1161540	5.15	5.87	.95	15		.409	.079	134
11615550	12.25				.33			
1161545	14.34	16.07	.98	13		1.137	.079	47
11615550	12.25				.92			
1161550	16.59	12.01	.98	10		1.029	.062	43
11615550	12.25				.84			
1161555	10.20	10.31	.98	13		.773	.076	66
11615550	12.25				.63			
1161560	10.74	9.50	.98	13		.829	.077	53
11615550	12.25				.67			
1161570	11.51	14.92	.98	13		.804	.070	88
11615550	12.25				.65			
1161709	9.77	18.74	.95	51		.667	.068	162
11617140	7.23				.92			
1161710	6.86	7.12	.96	9		.582	.085	80
11617140	7.23				.80			
1161718	8.15	7.11	.98	35		.612	.075	72
11617140	7.23				.84			

Table continued

1 CSU ID	2 Mean	3 Variance	4 Cor Cof	5 Case	6 Coeff	7 Increase Runoff	8 Increase Ratio	9 Years Eval.
1161720	2.78	2.96	.96	10		.243	.087	193
11617250	3.24				.74			
1161721	9.24	10.56	.98	10		.608	.066	109
11617250	3.24				1.87			
1161723	12.65	19.36	.97	10		.786	.062	120
11617250	3.24				2.42			
1161730	8.45	7.13	.98	20		.753	.089	48
11617350	9.95				.75			
1161734	11.07	11.03	.98	22		.916	.083	50
11617350	9.95				.92			
1161736	5.34	4.10	.97	13		.365	.068	118
11617350	9.95				.36			
1161737	13.49	18.09	.99	13		.995	.074	70
11617350	9.95				1.0			
1161753	2.82	2.34	.94	30		.246	.087	148
11617460	4.58				.53			
1161754	2.51	3.72	.915	18		.259	.103	212
11617460	4.58				.56			
1161755	5.52	10.98	.94	18		.567	.103	130
11617460	4.58				1.23			
1161756	.80	.43	.93	10		.065	.082	385
11617460	4.58				.14			
1161761	1.35	.42	.93	10		.101	.075	158
11617460	4.58				.22			
1161778	11.37	9.97	.98	27		.779	.069	63
11617460	4.58				1.70			
1161780	8.53	13.18	.96	11		.927	.109	58
11617460	4.58				2.02			
1161787	6.24	7.21	.97	19		.529	.085	98
11617460	4.58				1.15			
1161788	7.82	10.31	.97	19		.704	.090	79
11617460	4.58				1.53			
1161791	15.48	22.67	.97	17		1.034	.067	81
11617460	4.58				2.25			
1161793	17.13	21.22	.96	25		.950	.055	90
11617460	4.58				2.07			
1162205	5.07	4.23	.97	25		.416	.082	93
11622001	4.76				.87			
1162215	3.79	5.32	.92	10		.390	.103	134
11622001	4.76				.82			
1162225	7.92	15.39	.96	17		.785	.099	95
11622001	4.76				1.65			
1162235	5.40	6.93	.952	18		.539	.100	91
11622001	4.76				1.13			
1162240	7.69	10.24	.97	25		.633	.082	98
11622001	4.76				1.32			
1162285	9.30	13.09	.97	51		.680	.073	108
11622001	4.76				1.42			
1162275	11.28	18.31	.98	12		.655	.058	163
11622001	4.76				1.37			
1162280	10.73	19.62	.98	12		.590	.055	216
11622001	4.76				1.24			
1162620	6.30	24.73	.92	10		.539	.086	327
11623000	4.23				1.27			
1163212	3.78	2.79	.95	11		.306	.081	114
11632080	6.91				.44			
1163213	21.28	39.38	.97	11		1.419	.067	75
11632080	6.91				2.05			
1163214	6.18	5.14	.97	26		.435	.070	104
11632080	6.91				.63			
1163215	4.15	2.74	.94	10		.352	.085	84
11632080	6.91				.51			
1163216	3.35	2.75	.96	23		.326	.097	99
11632080	6.91				.47			

Table continued

1 CSU ID	2 Mean	3 Variance	4 Cor Coef	5 Case	6 Coeff	7 Increase Runoff	8 Increase Ratio	9 Years for Eval.
1163220	1.85	.68	.93	12		.200	.108	65
11632080	6.91				.28			
1163224	5.12	3.83	.96	33		.403	.079	90
11632080	6.91				.58			
1163225	11.29	11.01	.98	11		.233	.021	779
11632080	6.91				.33			
1163228	11.54	6.27	.98	12		.741	.064	43
11632610	9.20				.80			
1163230	24.53	45.29	.98	10		2.037	.083	41
11632610	9.20				2.21			
1163232	9.06	8.33	.98	22		.693	.076	66
11632610	9.20				.75			
1163234	7.39	6.53	.97	10		.763	.103	43
11632610	9.20				.82			
1163236	17.85	20.08	.98	10		1.492	.084	34
11632610	9.20				1.62			
1163237	32.67	58.32	.99	10		2.685	.082	31
11632610	9.20				2.91			
1163238	13.94	21.18	.98	10		.982	.070	84
11632610	9.20				1.06			
1163247	3.88	4.39	.94	12		.249	.064	271
11632610	9.20				.27			
1163249	7.09	4.68	.98	18		.464	.065	83
11632610	9.20				.50			
1163252	7.92	11.51	.97	11		.519	.066	164
11632610	9.20				.56			
1163253	10.67	14.78	.98	10		.703	.066	114
11632610	9.20				.76			
1163261	5.66	4.08	.97	10		.398	.070	98
11632610	9.20				.43			
1163263	8.39	9.97	.97	10		.719	.086	74
11632850	15.17				.47			
1163264	9.08	11.30	.97	11		.819	.090	64
11632850	15.17				.54			
1163265	9.23	9.40	.97	11		.812	.088	54
11632850	15.17				.53			
1163276	37.50	29.84	.99	10		3.475	.093	9
1162850	15.17				2.29			
1163282	32.81	65.43	.99	10		2.894	.088	30
11632850	15.17				1.90			
1163284	13.10	15.57	.98	10		1.335	.102	33
11632850	15.17				.88			
1163294	6.00	6.33	.98	10		.593	.099	69
11632850	15.17				.39			
1163296	8.53	.48	.99	10		.560	.066	5
11632850	15.17				.36			
1163298	14.59	9.02	.99	12	.84	1.279	.088	21
11632850	15.17							
1164400	5.69	7.27	.96	9		.188	.033	787
11648001	5.13				.36			
1164810	1.13	.46	.90	36		.052	.046	645
11648001	5.13				.10			
1164880	7.69	5.43	.96	22		.517	.067	78
11648001	5.13				1.00			
1165425	5.02	3.70	.92	15		.381	.076	98
11658000	4.00				.952			
1165430	5.68	6.10	.95	19		.405	.071	143
11654250	4.96				.81			
1165435	7.85	7.10	.94	12		.546	.070	91
11654250					1.10			
1165455	2.88	1.77	.92	16		.199	.069	171
11654250	4.96				.40			
1165465	6.38	2.91	.96	25		.370	.058	81
11654250	4.96				.74			

Table continued

1 CSU ID	2 Mean	3 Variance	4 Cor Cof	5 Case	6 Coeff	7 Increase Runoff	8 Increase Ratio	9 Years for Eval.
1165470	9.18	6.09	.96	25		.558	.061	75
11654250	4.96				1.12			
1165480	3.30	4.98	.89	18		.185	.056	561
11654250	4.96				.37			
1165485	10.78	5.11	.96	25		.685	.064	41
11654250	4.96				1.38			
1166236	10.45	8.17	.96	25		.573	.055	95
11662180	3.78				1.51			
1166254	2.85	1.07	.97	11		.257	.090	62
11662180	3.78				.67			
1166272	9.67	7.32	.95	25		.544	.056	94
11662180	3.78				1.44			
1166630	3.89	2.53	.93	13		.432	.111	52
11673000	3.85				1.12			
1167030	4.11	3.29	.94	9		.402	.098	78
11673000	3.85				1.04			
1167460	8.22	12.50	.96	15		.927	.113	55
11673000	3.85				2.40			
1167600	9.96	12.22	.933	33		.563	.057	147
11678450	5.29				1.06			
1167806	5.39	3.82	.97	10		.510	.095	56
11678450	5.29				.965			
1167809	11.93	14.20	.95	26		.590	.049	156
11678450	5.29				1.11			
1167815	14.90	16.93	.96	26		.753	.051	114
11678450	5.29				1.42			
1167818	18.41	45.45	.98	10		1.597	.087	68
11678450	5.29				3.01			
1167821	16.55	13.52	.96	25		.789	.048	83
11678450	5.29				1.49			
1167836	12.53	11.40	.95	26		.530	.042	156
11678450	5.29				1.00			
1167842	13.73	10.61	.96	26		.589	.043	117
11678450	5.29				1.11			
1167854	24.17	26.66	.98	10		1.789	.074	32
11678450	5.29				3.38			
1167875	15.72	4.06	.95	26		.650	.041	36
11678450	5.29				1.22			
1168060	3.64	5.59	.92	16		.418	.115	122
11690000	9.79				.42			
1168430	5.93	9.01	.96	23		.617	.104	90
11690000	9.79				.63			
1168460	17.90	31.07	.99	10		2.191	.122	24
11690000	9.79				2.23			
1168600	2.62	3.40	.90	16		.310	.118	135
11690000	9.79				.31			
1200000	.39	.05	.96	10		.037	.094	142
12100000	5.32				.06			
1203000	1.29	.55	.93	15		.122	.094	142
12100000	5.32				.22			
1206000	2.80	3.48	.93	10		.290	.104	158
12100000	5.32				.54			
1270800	2.38	2.18	.97	9		.220	.092	173
12100000	5.32				.41			
1272405	3.37	8.32	.91	10		.821	.244	47
12724602	16.59				.49			
1272425	1.78	1.26	.90	11		.196	.110	126
12724602	16.59				.11			
1272435	6.28	21.98	.94	10		1.083	.173	71
12724602	16.59				.65			
1272450	2.94	2.77	.91	10		.382	.130	73
12724602	16.59				.23			

Table continued

1	2	3	4	5	6	7	8	9
CSU ID	Mean	Variance	Cor Cof	Case	Coeff	Increase Runoff	Increase Ratio	Years Eval.
1273230	3.38	5.25	.93	10		.229	.068	384
12732001	6.09				.37			
1274830	.99	.41	.91	10		.066	.067	357
12732001	6.09				.10			
1276400	4.80	4.75	.93	10		.228	.048	349
12732001	6.09				.37			
1370300	6.49	8.42	.94	48		.444	.068	164
13715052	5.15				.86			
1371500	1.51	.56	.95	25		.128	.085	131
13715052	5.15				.24			
1371520	5.96	4.60	.96	52		.435	.073	93
13715052	5.15				.84			
1371545	11.94	16.67	.97	17		.956	.080	70
13715052	5.15				1.85			
1371550	7.81	6.02	.97	10		.617	.079	60
13715052	5.15				1.19			
1371560	22.06	8.79	.98	16		1.510	.068	14
13715052	5.15				2.93			
1371565	25.60	9.42	.98	10		1.814	.071	10
13715052	5.15				3.52			
1371570	21.86	12.93	.98	14		1.418	.065	24
13715052	5.15				2.75			
1371575	17.02	23.19	.98	10		1.360	.080	48
13715052	5.15				2.64			
1371815	15.20	29.11	.97	25		.926	.061	130
13715052	5.15				1.79			
1371835	7.01	11.41	.97	10		.540	.077	150
13718100	6.70				.80			
1371845	6.69	9.90	.97	10		.553	.083	124
13718100	6.70				.82			
1371855	12.15	22.83	.98	10		.888	.073	111
13718100	6.70				1.32			
1371870	7.03	11.23	.97	10		.509	.072	166
13718100	6.70				.76			
1371890	6.58	12.93	.96	10		.527	.080	179
13718100	6.70				.78			
1373020	15.36	28.04	.97	20		1.424	.093	53
13730212	9.62				1.48			
1373025	6.60	3.61	.98	11		.656	.099	32
13730212	9.62				.682			
1373080	7.16	16.08	.94	10		.367	.051	457
13730212	9.62				.38			
1373085	7.56	6.72	.97	19		.646	.085	61
13730212	9.62				.67			
1373360	11.35	20.96	.97	29		.941	.083	90
13730212	9.62				.97			
1374275	14.62	35.42	.99	10		.569	.039	420
13730212	9.62				.59			
1374800	11.13	20.70	.97	19		.746	.067	143
13730212	9.62				.77			
1375400	7.47	6.62	.96	27		.588	.079	73
13772400	8.71				.67			
1375750	11.61	30.69	.96	10		.822	.071	174
13772400	8.71				.94			
1376000	2.68	2.32	.90	18		.247	.092	145
13772400	8.71				.28			
1376050	4.93	6.15	.94	10		.313	.063	241
13772400	8.71				.35			
1377210	1.41	.63	.92	10		.179	.127	75
13772400	8.71				.20			
1377250	1.42	.64	.92	10		.131	.092	144
13772400	8.71				.15			
1377270	2.46	1.65	.94	10		.192	.078	171
13772400	8.71				.22			

Table continued

1	2	3	4	5	6	7	8	9
CSU ID	Mean	Variance	Cor Cof	Case	Coeff	Increase Runoff	Increase Ratio	Years for Eval.
1377280	3.99	3.13	.93	27		.225	.056	237
13775000	5.18				.43			
1377825	7.66	6.75	.98	10		.717	.044	50
13775000	5.18				1.38			
1377850	10.38	28.99	.92	10		.440	.042	574
13775000	5.18				.85			
1378130	12.36	14.51	.97	11		.828	.067	81
13781450	14.25				.58			
1378160	24.89	6.41	.96	10		1.743	.070	8
13781450	14.25				1.22			
1379000	6.88	5.08	.97	26		.540	.078	66
13781450	14.25				.37			
1420800	12.32	10.11	.98	23		1.178	.096	27
14250000	8.79				1.34			
1423260	7.26	4.74	.98	10		.757	.104	31
14250000	8.79				.86			
1424050	7.47	2.86	.98	13		.806	.108	16
14250000	8.79				.91			
1424820	16.58	14.51	.98	12		1.554	.094	23
14250000	8.79				1.76			
1425600	8.57	21.39	.96	9		.793	.093	130
14250000	8.79				.90			
1425625	4.11	4.58	.94	43		.431	.105	94
14250000	8.79				.49			
1425675	5.54	13.05	.91	10		.527	.095	180
14250000	8.79				.59			
1426400	13.09	27.35	.96	39		1.137	.087	81
14250000	8.79				1.29			
1428800	6.20	13.47	.93	10		.637	.103	127
14250000	8.79				.72			
1480000	7.36	16.22	.94	10		.645	.088	149
14900000	6.36				1.01			
1500000	5.68	5.92	.96	12		.683	.120	48
15963000	11.30				.60			
1510000	1.24	.13	.98	12		.113	.108	28
15963000	11.30				.11			
1515050	6.01	2.10	.97	10		.619	.103	21
15963000	11.30				.54			
1554500	5.34	7.13	.95	9		.655	.123	63
15963000	11.30				.58			
1556000	10.77	10.29	.95	9		1.259	.117	24
15963000	11.30				1.14			
1560000	3.80	5.50	.89	10		.297	.078	239
15963000	11.30				.26			
1570000	6.12	6.36	.94	10		.537	.088	84
15963000	11.30				.47			
1580000	11.70	19.26	.96	10		1.072	.092	64
15963000	11.30				.94			
1590700	6.15	8.57	.96	10		.793	.129	52
15963000	11.30				.70			
1594206	10.25	11.38	.97	10		.899	.088	54
15963000	11.30				.79			
1594218	9.85	12.10	.98	10		1.113	.113	37
15963000	11.30				.98			
1594224	19.34	31.31	.98	10		1.832	.095	35
15963000	11.30				1.62			
1594236	15.19	21.10	.97	17		.972	.064	85
15963000	11.30				.86			
1594260	15.84	20.25	.98	17		1.133	.072	60
15963000	11.30				1.06			
1660000	6.05	4.11	.97	18		.612	.101	42
166114001	6.14				.99			

Table continued

1	2	3	4	5	6	7	8	9
CSU ID	Mean	Variance	Cor Cof	Case	Coeff	Increase Runoff	Increase Ratio	Years for Eval.
1662150	5.18	3.83	.96	14		.532	.103	51
16614001	6.14				.86			
1662800	11.29	5.26	.98	14		.510	.045	77
16614001	6.14				.83			
1664900	14.82	12.99	.98	12		1.232	.083	32
16614001	6.14				2.00			
1664960	16.59	25.13	.97	9		1.370	.083	51
16614001	6.14				2.23			
1664980	22.61	28.80	.98	9		1.854	.082	32
16614001	6.14				3.02			
1666300	16.10	15.12	.98	20		1.442	.090	27
16614001	6.14				2.34			
1666350	2.32	.27	.98	10		.183	.079	30
16614001	6.14				.29			
1667000	11.91	12.57	.97	12		.925	.078	56
16614001	6.14				1.50			
1667700	8.79	10.01	.96	20		.713	.081	75
16614001	6.14				1.16			
1720000	10.14	11.70	.97	20		1.049	.103	40
17403000	8.56				1.22			
1742400	9.32	10.26	.96	12		.782	.084	64
17403000	8.56				.91			
1742700	17.09	9.82	.99	9		.966	.056	40
17403000	8.56				1.12			
1743000	15.62	11.87	.98	14		1.344	.086	25
17403000	8.56				1.57			
1743300	12.24	6.21	.97	9		.831	.068	34
17403000	8.56				.97			
1743600	11.76	4.83	.98	9		.876	.074	24
17403000	8.56				1.02			
1745160	10.07	8.48	.98	13		1.356	.135	17
17403000	8.56				1.58			
1752000	4.96	4.00	.95	10		.475	.096	68
17403000	8.56				.55			
1754000	11.02	12.19	.98	10		1.158	.105	34
17403000	8.56				1.35			
1758000	7.22	6.05	.96	10		.781	.108	38
17403000	8.56				.91			
1760000	2.86	1.50	.94	19		.275	.096	76
17403000	8.56				.32			
1767500	5.94	6.89	.96	11		.815	.137	39
17403000	8.56				.95			
1775000	13.60	5.41	.98	10		1.033	.076	19
17403000	8.56				1.20			
1776000	11.80	11.25	.97	31		.985	.083	44
18036000	10.69				.92			
1777000	14.91	37.97	.94	9		1.497	.100	65
18036000	10.69				1.40			
1780000	4.97	6.77	.91	10		.797	.160	40
17403000	8.56				.93			
1801808	8.24	7.45	.97	26		.557	.068	92
18036000	10.69				.52			
1817500	7.16	4.78	.98	19		.729	.102	34
18036000	10.69				.68			
1863000	19.16	12.37	.99	10		1.487	.078	21
18036000	10.69				1.39			

Key Words: Suitability, Upper Colorado River Basin, Precipitation Management, Evaluation, Optimal combinations

Abstract: The purpose of this study was the determination of suitable watersheds or combinations of watersheds for precipitation management programs in the Upper Colorado River Basin in general and for two special zones: the San Juan Mountains and the Upper Basin of the Colorado River. The study shows that the introduction of optimal weight factors in the linear combination of runoff from several basins will reduce significantly the number of years necessary for evaluation of the operations. Assuming a uniform 10% increase in winter precipitation throughout the Upper Colorado River Basin, the calculations show that three years of operations would be needed in the Upper Basin of the Colorado versus six years in the San Juan mountains

References: Hiroshi Nakamichi and Hubert J. Morel-Seytoux, Colorado State University Hydrology Paper No. 36 (October 1969) "Suitability of the Upper Colorado River Basin for Precipitation Management."

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PREVIOUSLY PUBLISHED PAPERS

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No. 24 "Application of Cross-Spectral Analysis to Hydrologic Time Series, by Ignacio Rodriguez-Iturbe, September 1967.

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Appendix 4

REGIONAL DISCRIMINATION OF CHANGE IN RUNOFF

REGIONAL DISCRIMINATION OF CHANGE IN RUNOFF

by

Viboon Nimmannit and Hubert J. Morel-Seytoux

November 1969

HYDROLOGY PAPERS
COLORADO STATE UNIVERSITY
Fort Collins, Colorado

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Several departments at Colorado State University have substantial research and graduate programs oriented to hydrology. These Hydrology Papers are intended to communicate in a fast way the current results of this research to the specialists interested in these activities. The papers will supply most of the background research data and results. Shorter versions will usually be published in the appropriate scientific and professional journals, or presented at national or international scientific and professional meetings and published in the proceedings of these meetings.

This research is part of a research project supported by the U.S. Department of Interior, Bureau of Reclamation, Office of Atmospheric Water Resources at Colorado State University with Dr. H. J. Morel-Seytoux as principal investigator, under contract numbered BR 14-06-D-6597.

REGIONAL DISCRIMINATION OF CHANGE IN RUNOFF

by
Viboón Nimmannit
and
Hubert J. Morel-Seytoux

HYDROLOGY PAPERS
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO 80521

November 1969 No. 37

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RELATION OF HYDROLOGY PAPER NO. 37 TO RESEARCH PROGRAM: "HYDROLOGY OF WEATHER MODIFICATION"

The present study is part of a more comprehensive project which has as one of its objectives the development of methods of evaluation of atmospheric water resources programs. Correlatively the application of the methods to a variety of basins forms a basis for selection of suitable watersheds, basins or regions.

Several approaches were pursued. This report discusses one of them. Several other approaches were previously described in Hydrology Papers 22, 34, and 36 (see back inside cover for complete reference).

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ABSTRACT

The object of this study is to find answers to the following questions:

What is the appropriate statistical test for a regional target-control technique of evaluation?

What is a suitable method for reduction of an originally large number of variables?

Which of the Upper Basin of the Colorado River or the San Juan Mountains is a more suitable area of operations, if the effectiveness of precipitation management is to be detected as quickly as possible?

The results of this research study show:

1. The T^2-test is the appropriate test for multiple target-control technique of evaluation.

2. The canonical analysis is the suitable method for the reduction of a large number of original variables.

3. The Upper Basin of the Colorado River is preferable under the assumption of an equal percentage of increase in runoff. However, if the percentage increase in the southern area is at least 1.2 times as large as in the northern area (and recent publications suggest that this ratio is probably around 3) then the southern area is preferable.

Based on the T^2-test, the minimum number of years for detecting an increase of 10 percent in spring runoff means are three years in the Upper Basin of the Colorado River, and four years in the San Juan Mountains.

REGIONAL DISCRIMINATION OF CHANGE IN RUNOFF

by

Viboon Nimmannit* and Hubert J. Morel-Seytoux**

Chapter I

INTRODUCTION

1.1 Motivation of study. As interference with nature is accelerating [1,2,3] there is a need for early detection of direct or side effects of man's actions. Because of the rapid pace of development [3, 4,5] it is important to develop techniques that will display the effect of any given practice on water resources availability and distribution at the earliest possible time. For large scale field research, the availability of an efficient and regionally representative test would reduce the duration of experiments required to attain conclusive results and therefore costs, and provide a basis for managerial decision at an earlier stage, without additional observations. The decision may be to stop a project earlier when it becomes apparent, based on real time analysis of data, that the objectives cannot be achieved in the planned time. Better, pre-experiment data simulation would permit to assess the chances of being in that unfortunate situation as a function of a range of values of the suspected or hoped for change. Useful charts can be drawn in terms of the parameters, (magnitude of change, basin characteristics, etc.) for first stage planning.

The techniques which are described in this paper could be used for detection of the effects of watershed management of any origin upon water supply. They could be used to determine the effect of urbanization on the local hydrology, to detect when such urbanization has created a significant change that calls for reappraisal of the protective designs, e.g., flood control, etc. In other words, they are quite general. To a certain degree the techniques will indeed be discussed in a general abstract form, but their practical applicability will be demonstrated with a very special and very important application in mind.

The Bureau of Reclamation will most probably initiate in the fall of 1970 a pilot project of massive cloud seeding operations, covering some 4000 square miles within the state of Colorado. It will be the primary purpose of this paper to establish as accurately as possible how long it will take to detect a regional hydrologic change and to attribute it with little risk of error to the cloud seeding operations. To understand this practical illustration of the technique some knowledge of the geographic and hydrologic features of the region, of the water situation and of the plans of the Bureau of Reclamation is a prerequisite. The purpose of the following sections is to provide this background information.

1.2 Geographic and hydrologic setting. The Colorado River begins high in the snow-capped Rocky Mountains of north central Colorado, flows nearly 1,400 miles southwest, and empties into the Gulf of California in Mexico far to the south. It drains a vast area of 244,000 square miles, 242,000 square miles in the United States--one-twelfth of the area of Continental United States--and 2,000 square miles in northern Mexico. The basin from Wyoming to below the Mexican border is some 900 miles long and varies in width from about 300 miles in the upper section to 500 miles in the lower section. It is bounded on the north and east by the Continental Divide in the Rocky Mountains, on the west by the Wasatch Range, and on the southwest by the San Jacinto Mountains, a range of the Sierra Nevada Mountains. The area, larger than the states of New York, Pennsylvania, and New Jersey combined, above Lee Ferry, Arizona, is known as the Upper Colorado River Basin (Fig. 1). This area is the source of the greatest part of water reaching the Colorado River. The upper portion of this basin in Wyoming and Colorado is a mountainous plateau, 5,000 to 8,000 feet in altitude, marked by broad rolling valleys, deep canyons, and intersecting mountain ranges. Climatologically, the Colorado River Basin has heavy precipitation on the high peaks of the Rockies and truly desert conditions with little rain in the southern area around Yuma, Arizona. Extremes of temperatures in the basin range from 50° below zero to 130° above zero degree Fahrenheit. Development and utilization of resources in this arid land depend on the availability of water. Crops must be irrigated; cattle on the vast ranges must be partially fed from hay produced on irrigated land; towns and cities must be located within distance of dependable domestic and municipal water supplies, and mining and many other industries depend, to an extent, on the availability of hydroelectric power [1].

1.3 The water resources outlook. The U.S. Geological Survey estimates total water demand in the United States was 280 billion gallons per day (314 million acre-feet per year) in 1960. As a point of comparison let us note that the average annual flow of the biggest river in the United States, the Mississippi, is 440 maf and that of the Upper Colorado is about 14 maf. The U.S.G.S. estimates the total water demand for the U.S. will be 600 billion gallon per day (672 million acre-feet per year) by 1980. In 1960 the demand in the Western States alone was estimated at 125 billion gallons per day (140 million

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Fig. 1 The Upper Colorado River Basin (after Upper Colorado River Commission)

acre-feet per year) and for 1980 at 190 billion gallons per day (213 million acre-feet per year). The lower percentage of demand growth for the Western States reflects different demands of industry in the East and agriculture in the West. Because rainfall is low in the Western States, the conservation use must be greater than in the East and Midwest. Municipal or domestic use has first priority in the West, with irrigation second. It is estimated the 44,000,000 population of the Western States in 1960 will expand to more than 100,000,000 by the year 2000 [2].

From the population figures given above, it is obvious much more water will be needed in the near future. So, the question one must answer is, "What can be used as sources for additional water to alleviate the shortages?" Several agencies, such as, the Bureau of Reclamation [3], the Upper Colorado River Commission [4], and the Committee on Water of the National Research Council [5], feel cloud seeding, to augment the precipitation amount in the Upper Colorado River Basin, may become a partial solution to the recurrent water shortage.

1.4 Precipitation management operations and plans. An important experimental cloud seeding operation is being conducted near Climax, Colorado, by Colorado State University under sponsorship of the National Science Foundation. These experiments are designed to show quantitative change in precipitation by cloud seeding and to determine criteria for optimum seeding conditions.

The most favorable conditions for cloud seeding are in regions where moist winds blow more or less constantly up the slopes of the mountains. Cloud seeding involves artificial introduction of tiny particles into clouds so that moisture can depose around each of the nuclei to form a crystal heavy enough to fall to the ground. Among nuclei that have been used experimentally in cloud seeding operations are solid carbon dioxide, silver iodide, water spray, and carbon black. To date, the greatest number of cloud-seeding attempts have been made by using silver iodide generators operated on the ground. However, seeding operations using aircraft flown directly over cloud layers have demonstrated that this technique may be more effective [6].

In 1968, the Bureau of Reclamation adopted a plan to start pilot programs for weather modification operations in the Upper Colorado River Basin (Fig. 1), and two regions were selected for this purpose [7]. The first was the Upper Basin of the Colorado River*, which will for brevity be referred to in this study as the Northern Project area (Fig. 2). The second area was the San Juan Mountains region referred to as the Southern Project area (Fig. 3). Since the initiation of this study, the plans of the Bureau were modified. Currently [8] only one area is considered: the Southern area. Nevertheless, because they had already been calculated, the results for the Northern area are also reported.

1.5 Objective of study and approach. The primary objective was to develop an appropriate and efficient methodology that can be used to demonstrate the effectiveness of cloud seeding in each project region. In order to achieve this, a multivariate analysis of geographically well distributed stations in each region is carried out. These stations are referred to as targets. Variables used in this study are spring runoffs. The spring runoff of a station is defined here as the average flow, in cubic feet per second, of that station during the spring months. Because this flow is substantially contributed by winter snow, it can be regarded as an indirect measure of the effect of weather modification. However, because of the lack of a precise date for the start of snow melting, two different time intervals will be used for spring months. The first interval will be composed of four months: April, May, June and July; the second of six months: March, April, May, June, July and August.

Because the use of controls, which are the stations free from the effect of weather modification, is a well proven means of making tests more effective, (9), it also will be utilized in this study. An area between the Northern and Southern Project areas has been selected (Fig. 4) to serve as the control area.

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*The reader is warned for possible confusion. In this paper the expression "Upper Colorado River Basin" refers to the Colorado Basin above Lee's Ferry. On the other hand, the expression "Upper Basin of the Colorado River" refers to a much smaller drainage basin including the main stem of the Colorado close to its source and a few tributaries. The limits of that basin are shown on Fig. 2.

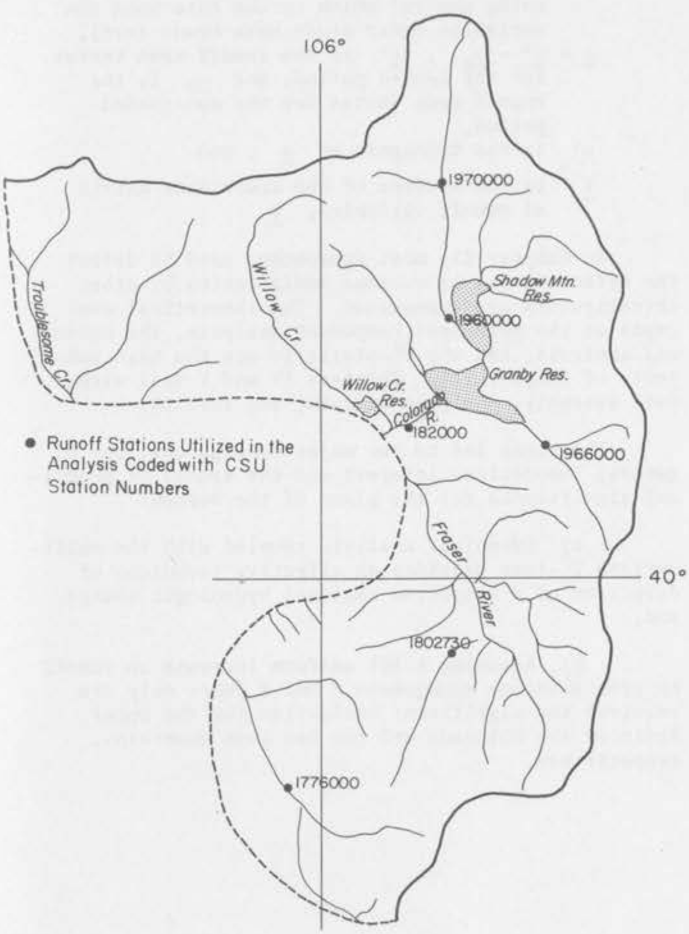


Fig. 2 General configuration of and location of gages within the Upper Basin of the Colorado River

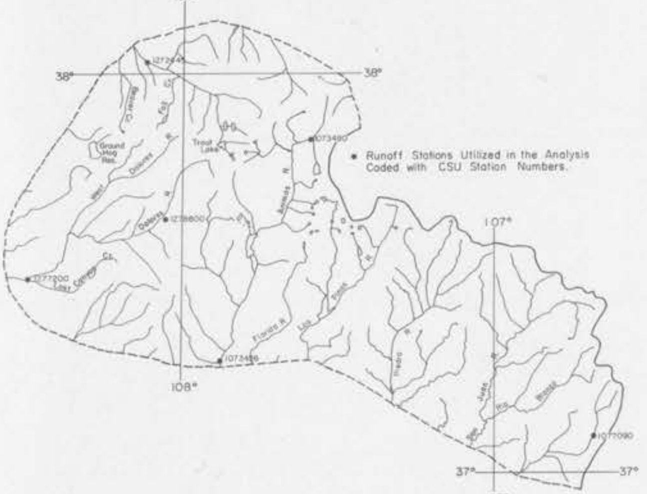


Fig. 3 General configuration of and location of gages within the Colorado River Basin Pilot Project area

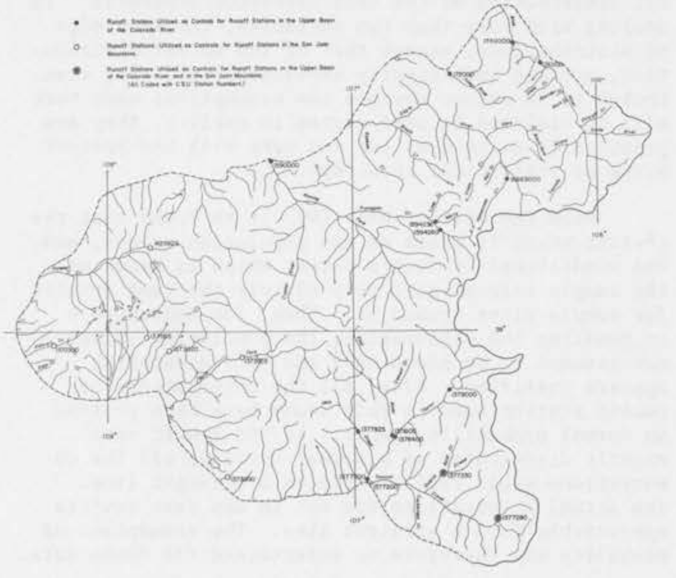


Fig. 4 General configuration of and location of gages within the Colorado River Basin Pilot Project control area

For brevity, the following symbols will be employed:

N-4:	4-month runoff series in the northern target region,
N-6:	6-month runoff series in the northern target region,
CN-4:	4-month runoff series in the northern control region,
CN-6:	6-month runoff series in the northern control region,
S-4:	4-month runoff series in the southern target region,
S-6:	6-month runoff series in the southern target region,
CS-4:	4-month runoff series in the southern control region,
CS-6:	6-month runoff series in the southern control region.
N-CN-4:	the combination of N-4 and CN-4,
N-CN-6:	the combination of N-6 and CN-6,
S-CS-4:	the combination of S-4 and CS-4,
S-CS-6:	the combination of S-6 and CS-6.

In applying theories of statistics to an engineering problem, it is necessary to assume certain properties of the variables. The assumptions made in this study are:

a) The observations of runoff follow a multivariate normal distribution.

b) The estimated means in both target and control areas from the period before seeding are essentially equal to the population values.

c) After seeding the means in the target areas will change but the means in the control areas will remain unchanged.

d) The covariance matrix of the target and control variables is the same for both periods before and after seeding.

The above assumptions are required in this study because of the difficulty in developing the theoretical distribution of the test criterion otherwise. In dealing with more than two variables, the knowledge of distributions, except that of the normal distribution, are not sufficiently developed [10]. So, even though it is rather obvious the assumptions made here will be violated to some degree in reality, they are practically as good as one can make with the present state of statistical knowledge.

From the work of Ref. [9], it is found that the χ^2-test which is based on the population values, and the conditional Student's t-test which is based on the sample values, give very closely the same results for sample sizes around 30. Thus, for convenience in handling the mathematics, the population values are assumed to be known here and this assumption appears justified. Also, all the observations of runoff station used in this study have been plotted on normal probability paper. If the runoff were exactly distributed as a normal variate, all the observations would fall exactly on a straight line. The actual observations did not in any case deviate appreciably from a straight line. The assumption of normality may therefore be entertained for these data.

Based on the above assumptions, a T^2-statistic is obtained [11,12]. The minimum number of years, N^*, to detect the expected increase can be obtained [11] from the formula,

$$N^* = \frac{\tau^2}{\underline{\mu}' \underline{V}^{-1} \underline{\mu}} \quad , \qquad (1)$$

where τ^2 is the noncentrality parameter (it is a measure of the amount of deviation from being central which is the case when the variables under study have means zero),

$\underline{\mu} = \underline{\mu}^* - \underline{\mu}_o$, $\underline{\mu}^*$ is the runoff mean vector for the seeded period, and $\underline{\mu}_o$ is the runoff mean vector for the non-seeded period,

$\underline{\mu}'$ is the transpose of $\underline{\mu}$, and

$\underline{V}^{-1}$ is the inverse of the covariance matrix of runoff variables, $\underline{V}$.

In Chapter II, most approaches used to detect the effectiveness of weather modification by other investigators are summarized. The theoretical concepts of the principal component analysis, the canonical analysis, and the T^2-statistic are the main subjects of Chapter III. Chapters IV and V deal with data assembly, analysis of data, and results.

The study led to two major conclusions, one of general theoretical interest and the second of practical significance for the plans of the Bureau:

a) Canonical analysis coupled with the multivariate T^2-test provides an effective technique of detection of a suspected regional hydrologic change and,

b) Assuming a 10% uniform increase in runoff by precipitation management 3 and 4 years only are required for significant evaluation for the Upper Basin of the Colorado and the San Juan Mountains, respectively.

Chapter II

REVIEW OF PREVIOUSLY USED TESTS

The statistical content of this chapter is not new. The material here is provided for the sake of convenience to a reader whose statistical background is that of the average engineer. A statistician can bypass this chapter without detrimental effect to the continuity and understanding of this paper.

In this chapter the statistical tests, which have been employed by other investigators for detecting the effectiveness of weather modification, will be presented. The literature is further discussed in Ref. 12. Because all tests are concerned with the expected increase in the means of either runoff or precipitation during the seeded period, the hypotheses for all tests can be stated as:

H_o (null hypothesis) - there is no increase in the mean of the hydrologic variable during the seeded period,

H_a (alternate hypothesis) - there is an increase in the mean.

2.1 Target sample u-test. Let $q_{11}, q_{12}, \ldots, q_{1n_1}$, be n_1 observations of a hydrologic variable for the nonseeded period, and $q_{21}, q_{22}, \ldots, q_{2n_2}$ be n_2 observations for the seeded period of a target watershed. When n_1 is large the mean and variance of the series $q_{11}, q_{12}, \ldots, q_{1n_1}$ can be considered to be the population mean and population variance. Assuming the variance of the seeded period is the same as the non-seeded period, the test statistic is [13]

$$u_o = \frac{\overline{q}_2 - \mu_1}{\sigma_1/\sqrt{n_2}} \quad ,$$

where u_o is normally distributed with mean o and variance 1

$$\overline{q}_2 = \frac{1}{n_2} \sum_{i=1}^{n_2} q_{2i}$$

$$\mu_1 = \frac{1}{n_1} \sum_{i=1}^{n_1} q_{1i}$$

$$\sigma_1^2 = \frac{1}{n_1} \sum_{i=1}^{n_1} (q_{1i} - \mu_1)^2 \quad .$$

The null hypothesis, H_o, will be accepted at a 5% level of significance if u_o has a value less than 1.645. That is, there is no increase in the mean. On the contrary, if u_o is greater than 1.645 the alternative hypothesis, H_a, will be accepted at a 5% level of significance. The use of this test can be found in References [9] and [14]. South Fork San Joaquin, California, was the target basin for the study in Reference [9]. There were 15 years of seeded record, and 29 years of non-seeded record. The apparent percentage increase in the mean of the seasonal runoff for the seeded period was about 10%. By the use of the target sample u-test it was found that $u_o = 1.20$. This shows that the target sample u-test was not powerful enough to detect the increase in mean value in the order of 10% of the old mean.

2.2 Target two-sample t-test. This test does not require knowledge of population parameters. Let $q_{11}, q_{12}, \ldots, q_{1n_1}$ and $q_{21}, q_{22}, \ldots, q_{2n_2}$ be n_1 and n_2 observations for the non-seeded and seeded periods of a target watershed.

Assuming the variances of the non-seeded and seeded periods are equal, the test statistic [15]

$$t_o = \frac{\overline{q}_2 - \overline{q}_1}{s\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}$$

is distributed as t-distribution with $n_1 + n_2 - 2$ degrees of freedom, where:

$$\overline{q}_1 = \frac{1}{n_1} \sum_{i=1}^{n_1} q_{1i}$$

$$\overline{q}_2 = \frac{1}{n_2} \sum_{i=1}^{n_2} q_{2i}$$

$$s^2 = \frac{\sum_{i=1}^{n_1} (q_{1i} - \overline{q}_1)^2 + \sum_{i=1}^{n_2} (q_{2i} - \overline{q}_2)^2}{(n_1 - 1) + (n_2 - 1)} \quad .$$

The use of this test can be found in References [8], [14], [16], [17], [18], [19], [20], [21], [22], [23], and [24]. The value of the t-statistic was also computed for South Fork San Joaquin [9] from the same set of data used in computing the target sample u_o. The computed t-statistic has the value of 0.89. So, again no significant increase was concluded. The target two-sample t-test, and the target sample u-test therefore can be considered to be insufficiently powerful tests for studies of this nature.

2.3 Target-control χ^2-test. The detectability of the test can be improved by the use of a control [9]. This can be done by comparing sets of hydrologic data of non-seeded and seeded periods for the target watershed with those for an unseeded control watershed located in the vicinity of the target area.

Let $q_{11}, q_{12}, \ldots, q_{1n_1}$ and $q'_{11}, q'_{12}, \ldots, q'_{1n_1}$ be n_1 observations for the period prior to seeding of the target and control watersheds respectively. Also, let n_2 observations for the seeded period in the target be denoted by $q_{21}, q_{22}, \ldots, q_{2n_2}$, and those in the control by $q'_{21}, q'_{22}, \ldots, q'_{2n_2}$.

When the length of record before seeding is long enough, the estimated statistics of the target and control can be assumed to be the population values. Assuming the variables in the target and control are bivariate normally distributed, then the test statistic [14]:

$$\chi_o^2 = \frac{n_2}{1-\rho^2}\left\{\left(\frac{\overline{q}_2-\mu_1}{\sigma}\right)^2 - 2\rho\,\frac{(\overline{q}_2-\mu_1)(\overline{q}'_2-\mu'_1)}{\sigma\,\sigma'} + \left(\frac{\overline{q}'_2-\mu'_1}{\sigma'}\right)^2\right\}$$

is distributed as Chi-square distribution with two degrees of freedom, where

ρ is the population coefficient of correlation between the target and control for the nonseeded period, given by

$$\rho = \frac{\sum_{i=1}^{n_1} (q_{1i}-\mu_1)(q'_{1i}-\mu'_1)}{\left[\sum_{i=1}^{n_1} (q_{1i}-\mu_1)^2 \sum_{i=1}^{n_1} (q'_{1i}-\mu'_1)^2\right]^{1/2}}$$

$$\mu_1 = \frac{1}{n_1}\sum_{i=1}^{n_1} q_{1i}$$

$$\mu'_1 = \frac{1}{n_1}\sum_{i=1}^{n_1} q'_{1i}$$

$$\overline{q}_2 = \frac{1}{n_2}\sum_{i=1}^{n_2} q_{2i}$$

$$\overline{q}'_2 = \frac{1}{n_2}\sum_{i=1}^{n_2} q'_{2i}$$

$$\sigma = \sqrt{\frac{1}{n_1}\sum_{i=1}^{n_1} (q_{1i}-\mu_1)^2}$$

$$\sigma' = \sqrt{\frac{1}{n_1}\sum_{i=1}^{n_1} (q'_{1i}-\mu'_1)^2} \;.$$

This test has been used in References [9] and [14].

With the use of Merced River at Pohono Bridge as a control runoff station for the target, South Fork San Joaquin, the observed χ_o^2-statistic was found to be [9] 22.2. The value of χ^2 for significance at 99% level of confidence is 9.2. Therefore, a significant increase was detected by the use of the target-control χ^2-test. This shows that for the same set of data for the target basin, the target-control χ^2-test is overwhelmingly more discriminating than the target two-sample t-test and the target two-sample u-test.

2.4 Target-control conditional Student's t-test. In this test population parameters are not known. What is tested is the normality or abnormality of the target, given the behavior of the control, normal or otherwise [9].

Let $q_{11}, q_{12}, \ldots, q_{1n_1}$ and $q_{21}, q_{22}, \ldots, q_{2n_2}$ be the n_1 and n_2 observations of a hydrologic variable in the target watershed before and during seeded periods respectively. Let $q'_{11}, q'_{12}, \ldots, q'_{1n_1}$ and $q'_{21}, q'_{22}, \ldots, q'_{2n_2}$ be the corresponding observations in the control watershed.

By application of the maximum-likelihood ratio method [25], the test statistic:

$$t_o = \frac{\dfrac{\sqrt{n_1+n_2-3}\left[(\overline{q}_2-\overline{q}_1)-(\overline{q}'_2-\overline{q}'_1)\left\{\sum_{i=1}^{n_1} a_i(\Delta q_{1i})+\sum_{i=1}^{n_2} b_i(\Delta q_{2i})\right\}\right]}{\left[\dfrac{1}{n_1}+\dfrac{1}{n_2}+\left(\dfrac{\overline{q}'_2-\overline{q}'_1}{\Delta}\right)^2\right]^{1/2}}}{\left[\sum_{i=1}^{n_1}(\Delta q_{1i})^2+\sum_{i=1}^{n_2}(\Delta q_{2i})^2-\left\{\sum_{i=1}^{n_1} a_i(\Delta q_{1i})+\sum_{i=1}^{n_2} b_i(\Delta q_{2i})\right\}^2\right]^{1/2}}$$

is obtained and it is distributed as Student's t-distribution with $n_1 + n_2 - 3$ degrees of freedom, where

$$\overline{q}_1 = \frac{1}{n_1}\sum_{i=1}^{n_1} q_{1i}$$

$$\overline{q}_2 = \frac{1}{n_2}\sum_{i=1}^{n_2} q_{2i}$$

$$\overline{q}'_1 = \frac{1}{n_1}\sum_{i=1}^{n_1} q'_{1i}$$

$$\overline{q}'_2 = \frac{1}{n_2}\sum_{i=1}^{n_2} q'_{2i}$$

$$(\Delta q_{1i}) = q_{1i} - \overline{q}_1$$

$$(\Delta q_{2i}) = q_{2i} - \overline{q}_2$$

$$(\Delta q'_{1i}) = q'_{1i} - \overline{q}'_1$$

$$(\Delta q'_{2i}) = q'_{2i} - \overline{q}'_2$$

$$\Delta^2 = \sum_{i=1}^{n_1} (\Delta q'_{1i})^2 + \sum_{i=1}^{n_2} (\Delta q'_{2i})^2$$

$$a_i = \frac{(\Delta q'_{1i})}{\Delta}$$

$$b_i = \frac{(\Delta q'_{2i})}{\Delta} \quad .$$

The use of this test can be found in References [9] and [14].

In Reference [9], the application of the target-control conditional Student's t-test was made for the target, South Fork San Joaquin, and the control, Merced River at Pohono Bridge. The observed t_0-statistic by this method was 3.80. The value of t for significance at 99% was 2.71. Therefore, a significant increase was the result of this test. Comparison of the results of the above mentioned statistic tests show that the target-control χ^2-test and the target-control conditional Student's t-test are better tests than the target two-sample t-test and the target sample u-test. Also note that for runoff data from high elevation watersheds the outcomes of the two tests are essentially the same for a sample size around 30. However, it should be noted that all these tests are applicable only when single target or single target-control technique is used. None of these tests can be applied without modification when the number of variables in the study is greater than two, which is the usual case.

2.5 Rank test. Let $q_{11}, q_{12}, \ldots, q_{1n_1}$ and $q_{21}, q_{22}, \ldots, q_{2n_2}$ be n_1 and n_2 observations of a hydrologic variable for the non-seeded and seeded periods respectively.

Arrange the observations in a common sequence of increasing magnitude,

$$q_{11}, q_{12}, q_{21}, q_{22}, q_{13}, q_{14}, q_{15}, q_{23}, q_{16}, \cdots .$$

Assign ranks from 1 to n , where $n = n_1 + n_2$, to the above sequence so that rank 1 is given to the smallest observation and n to the largest.

The test statistic is now [26]:

$$Z = \frac{T_s - \overline{T}}{\sigma} \quad ,$$

where Z is approximately a standard normal variate,
T_s is the sum of ranks for seeded observations,
$\overline{T}$ is the expected mean value of T_s , given by

$$\overline{T} = \frac{n_2(n_2 + n_1 + 1)}{2}$$

$$= \frac{n_2(n + 1)}{2} \quad ,$$

and $$\sigma = \sqrt{\frac{n_2 n_1 (n + 1)}{12}} \quad .$$

If Z is greater than 1.645, then, one rejects the null hypothesis and concludes that at the 5% level of significance weather modification was effective.

This test has been used in References [27] and [28]. From the data in the Necaxa Watershed, Mexico, it was found that [27] the value of Z was 2.64, which is a value significant beyond the 99% level. The numbers of observations were 45 seeded days and 29 unseeded days. However, the apparent increase in the mean of the seeded period here was large. The seeded mean was about 26 percent larger than the unseeded mean. So, the use of rank test in Reference [27] does not tell much about the efficiency of the test at all. In fact, with the amount of increase of this order, one can find with any statistical test that the cloud seeding is effective. For example, when the u-test is applied the approximate number of observations needed to detect the 26 percent increase in the mean is obtained from:

$$N^* = \frac{4\sigma^2}{h^2 \mu^2}$$

where N^* is the approximate number of observations required to detect a certain amount of increase in the mean,
σ^2 is the variance of the hydrologic variable for the unseeded period,
μ is the mean of the hydrologic variable for the unseeded period, and
h is the fractional increase in mean.

Upon substituting the values of σ^2 , μ , h from the data of Reference [27], it was found that

$$N^* = \frac{4 \times 600.17}{(.26)^2 (88.14)^2} \approx 5 \quad .$$

Thus, it is clear that the required number of observations to detect a 26 percent increase in the mean is much smaller than 45 which is the actual number of observations. So, with this large amount of increase any statistical test will always give the positive result.

2.6 Median test. The median of a distribution is that value which divides the distribution halfway, i.e., half the distribution have lower and half have higher values. The median test determines primarily if the medians of the populations from which the samples come are well separated or not.

Let $q_{11}, q_{12}, \ldots, q_{1n_1}$ and $q_{21}, q_{22}, \ldots, q_{2n_2}$ be n_1 and n_2 observations of a hydrologic variable for the non-seeded and seeded periods respectively. Arrange the observations in a common sequence of increasing magnitude, e.g.,

$$q_{11}, q_{12}, q_{21}, q_{22}, q_{23}, q_{13}, q_{14}, q_{15}, q_{16}, q_{24}, \cdots .$$

If the total number of observations is even, the median is taken to be halfway between the two middle observations. If this total number is odd, the median observation is removed since it does not contribute any information to the question of whether the distribution of that sample has its median above or below the joint sample median. The case then reduces to the even case.

Let the numbers of q_{1i}'s above and below the median of the common sequence be n_{1a} and n_{1b}, and the numbers of q_{2j}'s above and below the same common sample median be n_{2a} and n_{2b}. Under the null hypothesis that the two samples come from identical distributions, the proportion of each sample lying below any point should be the same.

If the test function [29]

$$M = (|2n_{1a}-(n_{1a}+n_{1b})|-1)^2/n_1+(|2n_{2a}-(n_{2a}+n_{2b})|-1)^2/n_2$$

is greater than $\chi^2_{0.95}$ with one degree of freedom, then, one rejects, at the 95% level, the hypothesis that the samples have the same median.

This test has been used in Reference [20]. The data used in Reference [20] were obtained from an experiment on artificial stimulation of rain in three climatologically similar regions, Delhi, Agra and Jaipur in northwest India. The net increase in rainfall obtained over all three regions was 41.9%. Thus, it was found that there was a highly significant increase in the amount of rainfall. The observations were made from 1957 to 1965 (excluding 1962) in Delhi, from 1960 to 1965 in Agra, and from 1960 to 1963 in Jaipur. There was, however, no observed statistic given in this report.

2.7 The Mann-Whitney U test. Let $q_{11}, q_{12}, \ldots, q_{1n_1}$ and $q_{21}, q_{22}, \ldots, q_{2n_2}$ be n_1 and n_2 observations of a hydrologic variable for the non-seeded and seeded periods respectively. Arrange the observations in a common sequence of increasing magnitude, e.g.,

$$q_{11}, q_{12}, q_{13}, q_{21}, q_{14}, q_{15}, q_{22}, q_{23}, q_{24}, \ldots .$$

The statistic U is defined as the number of times a q_{2j} precedes a q_{1i}. This test was used to test the null hypothesis

H_o - the q_{1i} and q_{2j} values have the same distribution against the alternative hypothesis,

H_a - the location parameter of q_{2j} is larger than the location parameter of q_{1i}, i.e., the bulk of the distribution of q_{2j}'s is to the right of the bulk of the distribution of q_{1i}'s.

If H_a is true, one expects U to be small. Mann and Whitney [30] computed tables that give probabilities associated with small (lower tail) values of U, and Auble [31] gives tables of critical values of U for significant levels of 0.001, 0.01, 0.025, and 0.05 for a one-sided test. For the one-sided alternative hypothesis that the location parameter of q_{2j} is smaller than the parameter of q_{1i}, one computes the statistic U', defined to be the number of times a q_{1i} precedes a q_{2j}, and uses Aubles's tables to test H_o.

The relationship between U and the sum of ranks for seeded observations, T_s, in the rank test can be expressed as (Wine [32]):

$$U = n_1n_2 + \frac{n_2(n_2+1)}{2} - T_s .$$

The U statistic is usually computed by the above equation, since it is tedious to compute from the definition of U when n_1 and n_2 become fairly large.

The test statistic is

$$W = \frac{U-\overline{U}}{\sigma} ,$$

where W is approximately a standard normal variate, $\overline{U}$ is the expected value of U, given by

$$\overline{U} = \frac{n_1n_2}{2} ,$$

and $\sigma = \sqrt{\dfrac{n_1n_2(n_1+n_2+1)}{12}}$.

If W is greater than 1.65, then the null hypothesis is rejected and one can conclude the location of q_{2j} is larger than that of q_{1i}. This test has been used by many authors - [20], [21], [28], [33], and [34].

In Reference [21], the data used were collected from a five-year period experiment (1960 through 1964) in Missouri. On comparing the average rainfall (inches/hour) of the seeded days with that of the non-seeded days, it was found there was, on the average, a decrease of 67.9%. The values of W ranged from smaller than 0.01 to 0.88. Thus, it was concluded that no evidence of increases in precipitation because of cloud seeding was achieved.

2.8 Run test. Let $q_{11}, q_{12}, \ldots, q_{1n_1}$ and $q_{21}, q_{22}, \ldots, q_{2n_2}$ be n_1 and n_2 observations of a hydrologic variable for the non-seeded and seeded periods respectively.

Arrange the observations in a common sequence of increasing magnitude, e.g.,

$$q_{11}, q_{12}, q_{21}, q_{13}, q_{14}, q_{22}, q_{23}, \ldots .$$

A run is defined as an unbroken sequence of elements of the same type, i.e., a sequence of q_{1i}'s or a sequence of q_{2j}'s. Let the number of runs be denoted by η. If two samples are from the same population, the non-seeded and seeded observations will be well mixed and the number of runs, η, will be large.

The test statistic is now [14]

$$U = \frac{\eta - \overline{\eta}}{\sigma} ,$$

where U is a standard normal variate, $\overline{\eta}$ is the expected value of η, given by

$$\bar{\eta} = \frac{2n_1n_2}{n_1+n_2}$$

$$\sigma = \sqrt{\frac{2n_1n_2(2n_1n_2-n_1-n_2)}{(n_1+n_2)^2(n_1+n_2-1)}} \quad .$$

If U is greater than 1.65, then the null hypothesis is rejected and the alternative hypothesis is accepted. This test has been used in Reference [35].

In Reference [35], the data of the King River at Piedra, California was analyzed. The observations were the annual flows from 1917 to 1954 for the non-seeded period, and 1955 to 1966 for the seeded period There was a decrease of about 3.3% in mean annual flows for the seeded period. The number of runs, η , was found to be 17, $\bar{\eta} = 19.240$, and $\sigma = 2.533$. From the above values, U was obtained as -0.88. Therefore, no significant increase in the mean annual flow was concluded.

Of all the tests stated above, it is found that none of them can be applied for testing the increase in runoff means when the number of runoff variables is greater than two. In the evaluation of weather modification effectiveness based on a multiple target-control concept the number of runoff variables involved is large. So, it is necessary to find an approach to detect the increase in means of these runoff variables.

In Chapter III, the principal components, canonical analysis, and the T^2-statistic are discussed.

Chapter III

PRINCIPAL, CANONICAL COMPONENTS AND THE T^2-STATISTIC

For small scale operations the method of evaluation of a significant change in hydrologic characteristics based on the single target-control concept is adequate. For large regions this procedure would not be very representative. Besides if the test were performed for many pairs of target and control it is not clear how one should treat the ensemble of the outcomes. On the other hand, there is no problem of interpretation when a single test is performed even though the tested statistic may itself be a complicated combination of many observations from many targets and controls. For representativity the station runoff variables should be geographically well distributed over the large area of interest. This results in a selection of a large number of variables that are usually not independent variables. Sometimes the number of variables involved may be so large that any study can hardly be made economically. In fact, this is one of the difficulties in this study since there are three big areas under investigation. It is, therefore, also an object of this study to find a suitable method for reducing the number of variables involved in the analysis.

There are several ways to reduce the number of variables. However, two methods are used here before the statistical test is carried out. One is the principal components analysis, the other the canonical analysis.

3.1 Principal component analysis. The principal components are linear combinations of random variables, which have special properties in terms of variances. Usually, the linear combination with the maximum variance is referred to as the first principal component; the second component is the one that is uncorrelated with the first and has the second largest variance, and so on. The idea of this analysis was discussed thoroughly by Hotelling [36] in 1933.

From the hydrologic point of view, these principal components can be considered as new transformed runoff variables though lacking simple physical meaning. These transformed variables have, in total, the same amount of fluctuation or variation as do the original runoff variables. But the number of the transformed variables can be smaller than that of the original variables. Also these transformed variables are independent while the original variables are not.

A priori what can be expected from the principal components analysis for the purpose of evaluation? Suppose the principal components analysis is carried for all the targets and all the controls. The first principal component for each group will be the most statistically representative single combination of targets and controls, respectively, because that combination will account for the largest fraction of the total variation. If the percentage is high (say 95%) all the other principal components can be dropped. Then the originally multivariate test reduces again to a familiar single target control t-test, even though the target variable and the control variable are each a combination of many target and control ones. The procedure will be simple and effective if the target first principal component and the control one are highly correlated. However, this need not happen because the targets and controls are treated separately and the procedure does not attempt to maximize the correlation between the two components (which canonical analysis does). It can be concluded that principal components analysis can provide the basis for a simple and highly representative test but it will not be, by far, a minimal time evaluation one. (The procedure for the actual computation of the principal components is summarized in Chapter V, Section 1).

3.2 The canonical analysis. Canonical analysis is a technique to maximize the correlations between two groups of random variables. This analysis gives new sets of transformed variables as linear combinations of the original runoff variables. The first linear combination of each group will have the highest correlation, and each is uncorrelated with the other linear combinations in its group. The second linear combinations will have the second highest correlation, the third linear combinations will have the third highest correlation and so on. These linear combinations are referred to as canonical variables or components.

In this study the first group is the group of runoff stations in the target region and the second group is made of stations in the control region. This analysis is particularly advantageous for evaluation purposes. The canonical analysis yields a smaller number of variables for the final test, and most importantly it also guarantees high correlations between the variables of the target and control regions.

3.3 Computation of canonical variables. The steps for computing the canonical variables are now described:

Step 1) Compute the covariance matrix, $\underline{\hat{V}}$, of the runoff variables of the two sets (target and control). For p_1 runoff stations in the target region and p_2 in the control region, then

$$\underline{\hat{V}} = \begin{bmatrix} \sigma_{11} & \sigma_{12} \cdots\cdots & \sigma_{1p_1} & \sigma_{1(p_1+1)} \cdots\cdots & \sigma_{1(p_1+p_2)} \\ \sigma_{21} & \sigma_{22} \cdots\cdots & \sigma_{2p_1} & \sigma_{2(p_1+1)} \cdots\cdots & \sigma_{2(p_1+p_2)} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \sigma_{p_1 1} & \sigma_{p_1 2} & \sigma_{p_1 p_1} & \sigma_{p_1(p_1+1)} \cdots\cdots & \sigma_{p_1(p_1+p_2)} \\ \sigma_{(p_1+1)1} & \sigma_{(p_1+1)2} \cdots & \sigma_{(p_1+1)p_1} & \sigma_{(p_1+1)(p_1+1)} \cdots & \sigma_{(p_1+1)(p_1+p_2)} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \sigma_{(p_1+p_2)1} & \sigma_{(p_1+p_2)2} \cdots & \sigma_{(p_1+p_2)p_1} & \sigma_{(p_1+p_2)(p_1+1)} \cdots & \sigma_{(p_1+p_2)(p_1+p_2)} \end{bmatrix} \qquad (2)$$

The subscripts of σ are the ordering numbers of the stations. The numbers 1 to p_1 are for the p_1 stations in the target region. The numbers p_1+1 to p_1+p_2 are for the p_2 stations in the control region. For example, the subscript 1 will refer to the first station in the target region, while the subscript p_1+1 will refer to the first station in the control region and the subscript p_1+2 the second station in the control region, etc.

σ_{ii} is the variance of the runoff series for station i , defined as,

$$\sigma_{ii} = \frac{1}{N} \sum_{s=1}^{N} (q_{is} - \overline{q}_i)^2 \quad , \tag{3}$$

where N is the number of years of recorded runoff data,

q_{is} is the s^{th} recorded runoff of station i, and

$\overline{q}_i$ is the mean of the recorded runoff of station i .

σ_{ij} is the covariance of stations i and j , defined as,

$$\sigma_{ij} = \frac{1}{N} \sum_{s=1}^{N} (q_{is} - \overline{q}_i)(q_{js} - \overline{q}_j) \tag{4}$$

$$\sigma_{ij} = \sigma_{ji} \quad .$$

Step 2) Partition the covariance matrix, $\underline{\hat{V}}$, such that,

$$\underline{\hat{V}} = \begin{bmatrix} \underline{\hat{V}}_{11} & \underline{\hat{V}}_{12} \\ \underline{\hat{V}}_{21} & \underline{\hat{V}}_{22} \end{bmatrix} \quad , \tag{5}$$

where $\underline{\hat{V}}_{11}$ is a $p_1 \times p_1$ matrix,

$$\underline{\hat{V}}_{11} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \cdots\cdots & \sigma_{1p_1} \\ \sigma_{21} & \sigma_{22} & \cdots\cdots & \sigma_{2p_1} \\ \vdots & \vdots & & \vdots \\ \sigma_{p_1 1} & \sigma_{p_1 2} & \cdots\cdots & \sigma_{p_1 p_1} \end{bmatrix} \tag{6}$$

$$\underline{\hat{V}}_{12} = \begin{bmatrix} \sigma_{1(p_1+1)} & \sigma_{1(p_1+2)} & \cdots\cdots & \sigma_{1(p_1+p_2)} \\ \sigma_{2(p_1+1)} & \sigma_{2(p_1+2)} & \cdots\cdots & \sigma_{2(p_1+p_2)} \\ \vdots & \vdots & & \vdots \\ \sigma_{p_1(p_1+1)} & \sigma_{p_1(p_1+2)} & \cdots\cdots & \sigma_{p_1(p_1+p_2)} \end{bmatrix} \tag{7}$$

$$\underline{\hat{V}}'_{12} = \underline{\hat{V}}_{21} \tag{8}$$

$$\underline{\hat{V}}_{22} = \begin{bmatrix} \sigma_{(p_1+1)(p_1+1)} & \sigma_{(p_1+1)(p_1+2)} & \cdots\cdots & \sigma_{(p_1+1)(p_1+p_2)} \\ \sigma_{(p_1+2)(p_1+1)} & \sigma_{(p_1+2)(p_1+2)} & \cdots\cdots & \sigma_{(p_1+2)(p_1+p_2)} \\ \vdots & \vdots & & \vdots \\ \sigma_{(p_1+p_2)(p_1+1)} & \sigma_{(p_1+p_2)(p_1+2)} & \cdots\cdots & \sigma_{(p_1+p_2)(p_1+p_2)} \end{bmatrix} \tag{9}$$

Step 3) Obtain the values of canonical correlations by solving the system,

$$\begin{vmatrix} -\theta\underline{\hat{V}}_{11} & \underline{\hat{V}}_{12} \\ \underline{\hat{V}}_{21} & -\theta\underline{\hat{V}}_{22} \end{vmatrix} = 0 \quad . \tag{10}$$

The values of θ are the canonical correlations.

Step 4) Let $\underline{\alpha}$ and $\underline{\gamma}$ be the column vectors of coefficients for the canonical variables of the target and control regions respectively. Then, for a given value θ_i , the vectors $\underline{\alpha}_i$ and $\underline{\gamma}_i$ can be obtained by solving the system,

$$\begin{bmatrix} -\theta_i\underline{\hat{V}}_{11} & \underline{\hat{V}}_{12} \\ \underline{\hat{V}}_{21} & -\theta_i\underline{\hat{V}}_{22} \end{bmatrix} \begin{bmatrix} \underline{\alpha}_i \\ \underline{\gamma}_i \end{bmatrix} = \underline{0} \tag{11}$$

subject to the standardization conditions:

$$\underline{\alpha}'_i \, \underline{\hat{V}}_{11} \, \underline{\alpha}_i = 1 \tag{12}$$

$$\underline{\gamma}'_i \, \underline{\hat{V}}_{22} \, \underline{\gamma}_i = 1 \quad ; \tag{13}$$

$\underline{\alpha}'_i$ and $\underline{\gamma}'_i$ are the transposes of $\underline{\alpha}_i$ and $\underline{\gamma}_i$ respectively.

Once the $\underline{\alpha}_i$ and $\underline{\gamma}_i$ are obtained, the canonical variables for the target region are obtained from the relations:

$$\zeta_i = \underline{\alpha}'_i \, \underline{Q}_1 \tag{14}$$

where ζ_i is the i^{th} canonical variable in the target region

$$\underline{\alpha}'_i = (\alpha_{i1}, \alpha_{i2}, \cdots , \alpha_{ip_1}) \tag{15}$$

$$\underline{Q}_1 = \begin{bmatrix} Q_1 \\ Q_2 \\ \vdots \\ Q_{p_1} \end{bmatrix} \tag{16}$$

$Q_1, Q_2, \ldots, Q_{p_1}$ are runoff variables in the target region.

Similarly, ε_i is the i^{th} canonical variable in the control region defined by the relation:

$$\varepsilon_i = \underline{\gamma}_i' \, \underline{Q}_2 \ , \tag{17}$$

where $\underline{\gamma}_i' = (\gamma_{i(p_1+1)} \gamma_{i(p_1+2)} \cdots \gamma_{i(p_1+p_2)})$ (18)

$$\underline{Q}_2 = \begin{bmatrix} Q_{p_1+1} \\ Q_{p_1+2} \\ \vdots \\ Q_{p_1+p_2} \end{bmatrix} \tag{19}$$

$Q_{p_1+1} , Q_{p_1+2} , \ldots, Q_{p_1+p_2}$ are runoff variables in the control region.

3.4 <u>The minimum number of years for detecting an increase in runoff means</u>. In the previous sections two techniques to transform the original runoff varibles were described and in the case of canonical analysis even the basic steps of the procedure were described. However, the multivariate T^2 test applies just as well for the set of original variables. The principal and canonical transformations will either simplify some of the calculations or improve the outcome of the test. Again, the transformations are not necessary to apply the test. Nevertheless in this study the test was only performed for the transformed variables.

Assuming the values of the population mean vector $\underline{\mu}^*$ and covariance matrix $\underline{V}$ for the seeded period are known, the minimum number of observations, N^* , that one needs in order to be able to reject the hypothesis $\underline{\mu}^* = \underline{\mu}_o$, where $\underline{\mu}_o$ is a given vector, is given by

$$N^* = \frac{\tau^2}{(\underline{\mu}^* - \underline{\mu}_o)' \ \underline{V}^{-1} \ (\underline{\mu}^* - \underline{\mu}_o)} \ , \tag{20}$$

where τ^2 is the noncentrality parameter with degrees of freedom k and $N-k$,
k is the total number of runoff variables, and
N is the number of observations for the non-seeded period.

Select values of τ^2 as given by Tang [37] and Lehmer [38] are shown for convenience in Table 1.

TABLE 1 - VALUE OF τ^2
Level of significance, $\alpha = 0.05$; power $\beta = 0.50$

Degrees of freedom		
k	N-k	τ^2
2	28	5.468
4	26	7.640
5	25	8.640
6	24	9.646
8	22	11.655

In this study the value of $\underline{\mu}_o$ is assumed to be the mean vector of target and control runoff variables for the period before seeding. $\underline{\mu}^*$ is similar to $\underline{\mu}_o$ except that the means of the target runoff variables are 1.1 times greater than those in $\underline{\mu}_o$. In other words, it is assumed in this study that the effect of precipitation management over the target areas will be to increase the runoff uniformly throughout the target areas by 10%. The covariance matrix $\underline{V}$ is assumed to be the same as that of the nonseeded period.

When the principal components (or the canonical variables) are used for computing N^* , then $\underline{\mu}^*$ and $\underline{\mu}_o$ are the mean vectors of the principal components (or the canonical variables) for the seeded and non-seeded periods respectively, and $\underline{V}$ is the covariance matrix of the principal components (or the canonical variables) for the non-seeded period. The original runoff variables can also be used in computing N^* . However, because of the large number of the original runoff variables, they are not used in this study.

It should be noted here that the use of principal components in equation (20) will yield approximately the same results as the use of the original runoff variables. This is due to the fact that the amount of variation accounted for by the principal components is practically the same as the variation of the original runoff variables. Thus, the principal component analysis will merely reduce the number of original variables, but will not improve the final outcome of the test.

However, if the number of variables can be reduced to one component then the principal component analysis will be very useful because one can apply a bivariate test, such as the conditional Student's t-test which is less restrictive in its assumptions than the T^2-test. Unfortunately, this usefulness will not be known until one has completed the analysis.

In the next chapter the collection of data in the Upper Basin of the Colorado River, the San Juan Mountains area, and the Maroon Peak and Grand Mesa region is discussed.

Chapter IV

RESEARCH DATA ASSEMBLY

The data used in this study are the records of the runoff from three regions in the Colorado River Basin. These are:

1. The Upper Basin of the Colorado River,
2. The San Juan Mountains area,
3. The Maroon Peak and Grand Mesa region.

The first two areas were originally [7] proposed as sites for extensive cloud seeding operation. They are called northern and southern target regions (Figs. 2 and 3), while the third is called the control region (Fig. 4). Currently [8] only one area is considered: the southern area. The selection of the control stations is done primarily on the basis of the high correlations with those in the target regions.

It is virgin flow, which is the flow free from any man-made intervention, that is necessary for this study. So, corrections must be made for the records of runoff. The records of runoff were obtained from U.S. Geological Survey Water Supply Papers. However, only the corrections due to transmountain, transbasin diversions, and regulation can be made. The diversion for irrigation cannot be made because there is no record for the amount of water diverted for this purpose. Thus, it is assumed after making the corrections above, that virgin flows are obtained.

Out of a large number of stations, seven stations are chosen for the final analysis in the northern target region, and six stations in the southern region. There are fourteen stations used as controls for the northern region, and nine stations as controls for the southern region. These stations and their descriptions are listed in Table 2. The correlations for these stations computed from all the corresponding actually available records are shown in Tables 3, 4, 5 and 6. There are two stations used as controls for both the northern and southern regions.

TABLE 2 - DESCRIPTION OF STATIONS

Types	Seq. No.	CSU Sta. No.	USGS Sta. No.	Names	Lat.			Long.			Area (Sq. Mi.)	Elevation (ft.)
					(o	'	")	(o	'	")		
Target-stations in Northern Project	1	1970000	9.0105	Colorado River below Baker Gulch, near Grand Lake, Colorado.	40	19	33	105	51	22	53	8750
	2	1960000	9.0110	Colorado River near Grand Lake, Colo.	40	13	08	105	51	25	103	8380
	3	1866000	9.0165	Arapaho Creek at Monarch Lake outlet, Colo.	40	06	45	105	44	57	47.1	8310
	4	1830000	9.0190	Colorado River below Lake Granby, Colo.	40	08	39	105	52	00	311	8050
	5	1820000	9.0195	Colorado River near Granby, Colo.	40	07	15	105	54	00	322	7960
	6	1802730	9.0265	St. Louis Creek near Fraser, Colo.	39	54	30	105	52	45	32.8	8980
	7	1776000	9.0360	Williams Fork near Leal, Colo.	39	49	55	106	03	20	89.5	8790
Control-stations for Northern Project	1	1742100	9.0535	Blue River above Green Mountain Reservoir, Colo.	39	49	55	106	13	20	514	7947
	2	1740000	9.0575	Blue River below Green Mountain Reservoir, Colo.	39	52	50	106	20	00	599	7683
	3	1720000	9.0595	Piney River near State Bridge, Colo.	39	48	00	106	35	00	82.6	7272
	4	1666300	9.0645	Homestake Creek near Red Cliff, Colo.	39	28	25	106	22	00	58.9	8783
	5	1594260	9.0780	Fryingpan River at Norrie, Colo.	39	19	50	106	39	30	89.5	8410
	6	1594236	9.0785	North Fork Fryingpan River near Norrie, Colo.	39	20	40	106	39	50	41.2	8400
	7	1590000	9.0850	Roaring Fork River at Glenwood Springs, Colo.	39	32	50	107	19	50	1460	5721
	8	1379000	9.1090	Taylor River below Taylor Park Reservoir, Colo.	38	48	50	106	36	40	254	9170
	9	1378400	9.1100	Taylor River at Almont, Colo.	38	40	00	106	51	00	477	8011
	10	1378100	9.1125	East River at Almont, Colo.	38	40	00	106	51	00	295	8006
	11	1377825	9.1135	Ohio Creek near Baldwin, Colo.	38	42	00	107	00	00	124	8180
	12	1377500	9.1145	Gunnison River near Gunnison, Colo.	38	32	50	106	57	00	1010	7670
	13	1377280	9.1155	Tomichi Creek at Sargents, Colo.	38	24	00	106	25	00	155	8420
	14	1377230	9.1180	Quartz Creek near Ohio City, Colo.	38	33	35	106	38	10	106	8430
Target-stations in Southern Project	1	1278800	9.1650	Dolores River below Rico, Colo.	37	38	20	108	03	35	105	8422
	2	1278050	9.1665	Dolores River at Dolores, Colo.	37	28	00	108	30	00	556	6919
	3	1272445	9.1725	San Miguel River near Placerville, Colo.	38	02	05	108	07	15	308	7056
	4	1077090	9.3440	Navajo River at Banded Peak Ranch, near Chromo, Colo.	37	05	07	106	41	20	69.8	7941
	5	1073480	9.3575	Animas River at Howardsville, Colo.	37	50	00	107	36	00	55.9	9617
	6	1073436	9.3615	Animas River at Durango, Colo.	37	16	45	107	52	47	692	6502
Control-stations for Southern Project	1	1425625	9.0975	Buzzard Creek near Collbran, Colo.	39	16	20	107	51	00	139	6955
	2	1577280	9.1155	Tomichi Creek at Sargents, Colo.	38	24	00	106	25	00	155	8420
	3	1377230	9.1180	Quartz Creek near Ohio City, Colo.	38	33	35	106	38	10	106	8430
	4	1377200	9.1190	Tomichi Creek at Gunnison, Colo.	38	31	20	106	56	25	1020	7629
	5	1373900	9.1275	Crystal Creek near Maher, Colo.	38	33	05	107	30	20	42.2	8070
	6	1373055	9.1325	North Fork Gunnison River near Somerset, Colo.	38	55	45	107	26	55	521	6039
	7	1373020	9.1345	Leroux Creek near Cedaredge, Colo.	38	55	35	107	47	35	35.1	7160
	8	1371815	9.1430	Surface Creek near Cedaredge, Colo.	38	59	00	107	51	00	26.7	8180
	9	1370300	9.1520	Kannah Creek near Whitewater, Colo.	38	59	00	108	14	00	61.9	—

TABLE 3 - CORRELATION MATRIX BETWEEN N-4 AND CN-4 (as computed from all available data)

			N-4						
		CSU STA. No.	1970000	1960000	1866000	1830000	1820000	1802730	1776000
	CSU STA. No.	USGS STA. No.	9.0105	9.0105	9.0110	9.0165	9.0190	9.0265	9.0360
CN-4	1742100	9.0535	.8625	.8365	.8375	.8234	.6475	.7779	.9342
	1740000	9.0575	.6055	.7277	.6970	.7077	.4634	.8427	.8357
	1720000	9.0595	.9164	.9003	.8322	.8476	.7171	.6076	.9470
	1666300	9.0645	.6781	.7548	.8147	.8304	.6023	.6515	.8033
	1594260	9.0780	.8952	.8514	.8854	.8919	.7218	.6618	.9219
	1594236	9.0785	.8608	.8567	.9187	.9089	.7975	.6291	.8647
	1590000	9.0850	.8723	.8776	.8382	.8770	.7701	.6381	.8717
	1379000	9.0190	.8364	.8174	.7846	.8541	.6999	.4699	.9080
	1378400	9.1100	.8474	.8434	.7942	.8473	.7329	.5012	.7744
	1378100	9.1125	.8635	.8151	.7971	.8301	.6581	.6456	.7896
	1377825	9.1135	.8741	.6554	.5844	.7306	.5222	.6190	.7672
	1377500	9.1145	.8714	.8338	.7996	.8434	.6851	.5337	.8012
	1377280	9.1155	.8026	.6197	.7937	.8009	.6634	.5672	.7082
	1377230	9.1180	.8644	.6436	.7113	.7675	.6274	.5090	.7536

TABLE 4 - CORRELATION MATRIX BETWEEN N-6 AND CN-6 (as computed from all available data)

			N-6						
		CSU STA. No.	1970000	1960000	1866000	1830000	1820000	1802730	1776000
	CSU STA. No.	USGS STA. No.	9.0105	9.0110	9.0165	9.0190	9.0195	9.0265	9.0360
CN-6	1742100	9.0535	.6648	.9578	.9124	.9243	.9937	.5921	.9155
	1740000	9.0575	.7233	.4359	.8704	.8640	.9038	.4789	.8409
	1720000	9.0595	.6944	.3230	.5386	.6146	.3806	.3611	.3126
	1666300	9.0645	.7348	.6093	.5738	.5336	.3514	.3718	.6702
	1594260	9.0780	.4923	.5923	.6371	.7567	.8406	.5299	.7359
	1594236	9.0785	.7153	.5548	.8017	.6039	.2842	.3247	.4008
	1590000	9.0850	.7877	.3323	.6076	.6012	.7616	.5203	.5695
	1379000	9.0190	.6576	.5072	.6912	.2488	.4766	.5284	.7748
	1378400	9.1100	.7135	.4373	.5538	.7051	.3055	.5282	.7908
	1378100	9.1125	.3529	.4010	.7701	.1470	.4582	.4277	.4510
	1377825	9.1135	.6645	.2784	.6396	.7202	.0136	.7097	.4439
	1377500	9.1145	.7503	.4247	.5132	.5766	.5478	.4155	.8483
	1377280	9.1155	.7354	.5034	.6163	.5225	.4351	.4590	.8899
	1377230	9.1180	.8004	.5576	.1133	.6640	.6830	.6961	.4868

TABLE 5 - CORRELATION MATRIX BETWEEN S-4 AND CS-4 (as computed from all available data)

			S-4					
		CSU STA. NO.	1278800	1278050	1272445	1077090	1073480	1073436
	CSU STA. NO.	USGS STA. NO.	9.1650	9.1665	9.1725	9.3440	9.3440	9.3615
CS-4	1425625	9.0975	.9004	.8519	.8872	.7978	.8466	.8258
	1377280	9.1155	.9020	.7565	.8040	.7529	.8295	.7353
	1377230	9.1180	.9108	.7289	.5841	.6336	.7553	.6964
	1377200	9.1190	.9865	.8587	.8428	.7859	.8895	.8423
	1373900	9.1275	.8879	.8710	.9059	.7988	.8578	.8549
	1373055	9.1325	.8900	.8599	.7981	.7835	.8582	.8216
	1373020	9.1345	.8335	.8608	.7064	.8226	.8118	.8069
	1371815	9.1430	.8961	.8993	.8021	.8490	.2168	.4315
	1370300	9.1520	.9299	.8058	.8909	.8576	.8276	.7837

TABLE 6 - CORRELATION MATRIX BETWEEN S-6 AND CS-6 (as computed from all available data)

			S-6					
		CSU STA. NO.	1278800	1278050	1272445	1077090	1073480	1073436
	CSU STA. NO.	USGS STA. NO.	9.1650	9.1665	9.1725	9.3440	9.3575	9.3615
CS-6	1425625	9.0975	.8217	.6427	.7111	.6302	.8128	.3267
	1377280	9.1155	.9310	.9100	.7033	.3573	.9009	.9126
	1377230	9.1180	.8008	.8536	.7309	.7921	.7754	.8297
	1377200	9.1190	.8864	.7361	.8601	.9381	.9729	.7719
	1373900	9.1275	.9406	.7605	.8115	.7576	.7964	.7121
	1373055	9.1325	.9368	.7148	.8990	.8423	.8881	.9498
	1373020	9.1345	.8947	.6922	.8129	.5556	.8410	.6934
	1371815	9.1430	.8844	.8071	.7831	.7217	.7546	.7877
	1370300	9.1520	.7872	.7429	.6865	.7834	.8869	.7467

The major part of the spring runoff will occur because of the melting of the winter snow, which is subject to the effect of seeding during winter time. So, it is reasonable to consider whatever changes in the value of the spring runoff as an indirect indicator of the effect of cloud seeding. This is equivalent to saying a larger amount of snowfall in winter will produce a larger amount of runoff in spring. Because of the uncertainty of the start of snow melting, both the runoff during the four months of April, May, June and July, and during the six months of March, April, May, June, July and August are used. These four-month runoff and six-month runoff periods are treated separately in this analysis.

The number of years of record for all stations is fixed at 30, starting from 1938 up to 1967. To assure that these stations are still in operation, the selection has been made in such a way that only stations that have records available for 1967 are considered. It is not likely that the operation of these stations will be discontinued in the near future.

The characteristics of the data used in this study are shown in Tables 7, 8, 9, 10, 11, 12, 13, and 14. There are some data missing in the runoff record of the stations selected but they are filled in by the regression method [39] with the random component superimposed. These stations with missing data are shown in Table 15. Also shown in Table 15 are the stations used in evaluating the missing data. Graphical representations of the data used are shown in Figs. 5, 6, 7, 8, 9, 10, 11, and 12 according to the regions. The means and standard deviations computed from the year 1938 up to 1967 data are shown in Table 16; and the correlations between N-4 and CN-4, N-6 and CN-6, S-4 and CS-4, and S-6 and CS-6 are shown in Tables 17, 18, 19, and 20, respectively.

In Chapter V, the analysis of the data and the results are presented.

TABLE 7 - N-4 SERIES (CFS)

	Station Numbers						
CSU	1970000	1960000	1866000	1830000	1820000	1802750	1776000
USGS	9.0105	9.0110	9.0165	9.0190	9.0195	9.0265	9.0360
Year							
1938	180.35	366.27	244.61	1175.06	1136.39	102.10	379.77
1939	216.18	245.75	129.61	754.37	763.81	72.41	247.57
1940	139.53	195.02	168.37	686.57	673.55	53.67	175.59
1941	163.66	251.27	318.69	994.23	805.08	70.50	224.29
1942	216.65	219.05	253.59	1192.95	850.85	83.66	282.53
1943	180.00	230.67	145.06	585.11	807.90	93.99	245.73
1944	191.33	224.75	170.59	661.96	728.79	73.77	218.40
1945	217.40	251.49	196.92	1069.87	837.71	72.80	233.42
1946	195.31	179.08	201.58	662.49	641.57	73.00	226.57
1947	200.72	317.40	246.16	1556.30	1035.65	98.51	317.40
1948	57.75	198.77	161.58	1023.12	682.34	74.82	231.42
1949	302.87	306.21	244.28	1069.03	1037.22	84.06	268.34
1950	170.28	180.74	155.98	923.67	246.07	72.07	227.35
1951	252.28	305.83	245.08	1000.46	992.64	107.37	301.82
1952	244.13	352.67	285.75	1188.94	1188.71	107.45	334.81
1953	235.87	207.48	186.89	740.89	737.48	75.53	225.97
1954	108.06	112.48	129.00	529.51	486.97	34.57	108.27
1955	145.96	150.63	171.09	749.74	438.18	52.04	163.22
1956	206.35	249.24	215.13	1046.18	874.92	42.58	219.86
1957	274.13	368.69	320.64	1625.95	1252.69	84.12	306.48
1958	226.14	249.54	220.52	929.26	995.11	80.32	247.84
1959	171.07	206.87	204.50	853.75	578.10	25.05	201.92
1960	212.75	280.40	217.77	1122.92	1384.95	43.85	252.19
1961	181.57	202.94	171.29	836.40	825.74	25.22	178.74
1962	268.49	373.30	229.44	1211.50	1108.41	48.16	313.24
1963	150.16	151.40	158.76	655.72	636.17	21.13	100.42
1964	195.19	198.73	177.40	826.43	810.51	22.48	177.83
1965	271.50	311.11	264.29	1193.47	1180.51	39.82	275.53
1966	141.71	125.82	99.35	288.08	272.07	20.50	142.67
1967	235.42	243.04	103.79	798.78	788.61	36.67	211.29

TABLE 8 - N-6 SERIES (CFS)

	Station Numbers						
CSU	1970000	1960000	1866000	1830000	1820000	1802750	1776000
USGS	9.0105	9.0110	9.0165	9.0190	9.0195	9.0265	9.0360
Year							
1938	126.75	258.12	171.72	806.46	857.32	75.53	269.28
1939	152.42	172.51	91.96	499.87	539.45	53.70	176.43
1940	97.59	135.77	121.40	456.37	479.85	40.21	126.53
1941	114.87	176.89	228.03	683.28	571.12	53.16	162.34
1942	152.78	153.63	166.17	837.27	597.26	62.61	202.05
1943	127.65	164.24	104.99	379.78	578.21	69.92	180.20
1944	133.58	155.78	121.51	426.60	511.21	55.45	157.48
1945	159.34	188.16	149.80	773.27	637.78	61.19	183.51
1946	139.16	128.65	143.48	447.69	466.07	55.12	164.47
1947	143.83	228.14	176.76	1116.29	752.17	76.19	237.03
1948	39.11	140.56	114.31	714.13	482.15	55.95	166.26
1949	215.43	216.55	172.61	735.79	731.75	63.60	195.86
1950	119.74	127.12	109.07	638.61	178.45	53.53	163.16
1951	185.38	228.48	177.25	723.93	718.66	80.43	221.28
1952	175.29	253.57	205.26	853.98	854.73	81.65	244.36
1953	171.42	154.66	136.06	543.19	542.88	58.32	169.56
1954	77.05	82.52	91.46	377.96	359.63	26.67	80.90
1955	105.61	112.60	123.39	540.96	319.30	41.40	125.25
1956	144.56	177.11	152.30	735.35	621.87	33.12	159.23
1957	201.40	273.95	234.88	1176.83	904.12	59.48	229.80
1958	157.49	175.79	154.87	644.97	710.91	57.91	177.54
1959	123.44	151.96	148.11	618.79	422.89	20.29	147.68
1960	150.52	199.93	153.26	780.54	993.41	31.58	180.31
1961	130.37	148.48	124.20	599.67	589.04	19.44	133.18
1962	193.05	269.76	164.31	851.17	762.64	35.21	225.39
1963	112.60	119.22	120.65	493.81	477.88	16.44	79.02
1964	141.14	146.24	128.08	589.81	575.56	18.43	130.85
1965	196.22	227.93	193.31	760.73	749.85	33.52	209.79
1966	101.45	93.69	74.06	109.61	95.96	17.30	106.26
1967	166.64	175.08	135.65	409.44	399.60	27.09	153.62

TABLE 9 - CN-4 SERIES (CFS)

	Station Numbers													
CSU	1742100	1740000	1720000	1666300	1594260	1594236	1590000	1379000	1378400	1378100	1377825	1377500	1377280	1377230
USGS	9.0535	9.0575	9.0595	9.0645	9.0780	9.0785	9.0850	9.1090	9.1100	9.1125	9.1135	9.1145	9.1155	9.1180
Year														
1938	1553.47	1425.34	268.05	201.44	335.55	67.04	3970.41	431.36	787.47	909.49	196.74	1327.83	142.26	147.15
1939	684.33	1141.80	226.68	203.33	354.16	142.06	2339.75	337.54	544.07	574.20	177.54	1514.84	111.77	92.95
1940	766.92	809.29	2.00	149.42	260.23	106.91	1747.83	213.23	302.13	427.80	102.24	1026.65	35.15	48.25
1941	1023.03	1020.70	184.80	178.80	235.00	145.17	2740.32	382.29	592.46	822.97	252.74	21.26	157.12	129.47
1942	1398.12	1191.44	100.01	107.32	245.19	114.37	3125.42	470.89	764.47	754.52	229.56	3676.62	211.14	193.06
1943	619.19	1234.40	61.42	209.79	306.11	164.67	2943.42	451.96	720.99	816.08	272.66	1167.75	148.61	142.62
1944	807.17	973.33	250.99	199.29	277.45	164.86	2897.58	372.48	587.09	774.26	274.26	1700.92	147.20	90.74
1945	865.43	1050.51	194.62	193.80	239.87	139.00	2763.15	333.35	490.27	700.26	220.31	1337.85	112.58	88.16
1946	867.13	983.65	169.00	199.61	342.19	121.38	2476.55	326.24	490.30	632.29	157.63	1143.95	60.34	61.08
1947	1322.76	1516.34	246.24	256.92	408.12	139.61	3720.75	501.64	755.42	902.67	259.66	1846.62	147.52	136.91
1948	1076.73	1238.84	218.43	222.78	340.15	130.56	3399.91	525.59	802.91	941.12	313.44	2022.60	153.99	128.68
1949	1133.94	1322.54	209.23	246.43	362.99	157.57	3093.04	472.44	758.16	824.38	265.90	1782.76	177.18	139.93
1950	926.02	1124.04	156.12	202.52	277.07	103.50	2489.05	354.75	543.50	729.29	216.72	1350.09	73.22	84.37
1951	1377.80	1558.42	200.49	265.24	363.02	148.72	2777.03	397.45	605.49	781.07	210.68	1456.51	120.06	86.09
1952	1298.34	1549.32	270.03	269.57	392.33	176.25	4112.90	629.16	1056.48	1228.04	381.88	2580.67	223.94	178.77
1953	982.09	1156.54	156.10	207.93	285.07	138.78	2476.33	378.85	609.77	648.70	110.59	1545.06	160.10	143.88
1954	455.33	518.35	68.95	108.61	156.27	60.74	1268.37	286.50	415.92	571.21	160.29	712.17	33.35	69.57
1955	595.77	726.05	133.83	157.44	233.58	93.63	1950.25	321.17	471.66	538.06	122.31	1027.53	53.45	100.22
1956	1019.09	1226.45	170.76	230.74	283.36	133.35	2384.36	412.39	620.21	696.76	218.34	1402.35	98.93	101.35
1957	1339.02	1588.86	290.43	323.31	477.71	246.11	5117.86	765.81	1308.94	1415.11	554.87	3221.64	278.21	216.48
1958	969.24	1167.64	229.26	200.47	298.62	131.64	2725.42	365.70	668.05	861.16	266.45	1704.05	189.82	141.25
1959	805.53	975.27	169.04	189.39	249.38	109.71	2287.30	290.53	419.22	492.07	144.33	940.66	74.47	93.10
1960	865.45	1029.95	182.68	200.25	285.94	130.83	2406.42	418.06	638.63	585.98	177.17	1278.18	122.16	105.95
1961	599.61	727.52	111.20	139.84	209.11	83.65	1768.37	294.09	436.30	477.45	129.08	913.05	90.66	68.80
1962	1084.42	1346.70	201.43	241.40	374.85	162.43	3686.80	597.80	992.49	1048.02	306.57	2343.79	163.82	148.87
1963	422.88	535.25	84.07	151.78	178.74	85.67	1413.14	253.52	355.39	417.41	81.39	791.08	57.07	53.86
1964	577.11	396.76	138.68	171.43	256.81	100.15	2240.17	298.35	473.43	563.00	136.31	1108.08	123.24	86.33
1965	1259.69	653.70	261.83	286.15	309.81	173.93	3707.54	598.89	1000.70	918.40	350.96	2574.95	193.54	168.81
1966	427.33	520.84	121.10	110.60	202.57	77.59	1833.54	317.30	483.67	524.86	134.20	1034.07	66.46	74.56
1967	624.37	588.06	162.84	59.72	265.00	107.42	2320.36	381.22	562.37	708.26	154.24	1308.58	44.29	78.78

TABLE 10 - CN-6 SERIES (CFS)

	Station Numbers													
CSU	1742100	1740000	1720000	1666300	1594260	1594236	1590000	1379000	1378400	1378100	1377825	1377500	1377280	1377230
USGS	9.0535	9.0575	9.0595	9.0645	9.0780	9.0785	9.0850	9.1090	9.1100	9.1125	9.1135	9.1145	9.1155	9.1180
Year														
1938	1156.86	1054.07	184.23	140.66	239.33	44.61	2879.64	318.79	583.73	653.26	139.83	963.01	103.19	108.20
1939	512.72	830.52	156.10	141.35	254.00	98.28	1699.53	264.92	409.91	416.61	127.55	1112.28	82.40	71.45
1940	576.41	604.49	.46	103.25	186.31	74.01	1275.78	164.25	236.45	310.62	74.91	769.56	43.81	39.15
1941	766.62	757.80	127.32	124.66	164.67	99.70	1998.73	283.64	440.50	588.59	176.72	15.10	113.88	96.58
1942	1039.55	874.05	67.08	136.77	171.51	77.86	2255.84	350.01	565.74	539.18	161.07	2665.26	150.62	140.25
1943	492.25	933.16	47.19	151.81	225.05	116.98	2244.66	347.56	556.40	599.26	200.14	902.68	109.85	108.00
1944	595.34	711.86	172.50	138.46	198.27	114.46	2098.35	277.19	441.90	555.34	192.79	1248.25	106.73	68.86
1945	726.18	856.90	138.97	148.88	179.62	100.35	2137.63	262.68	397.07	521.22	164.32	1046.98	85.38	72.17
1946	660.20	735.90	119.43	138.42	245.65	83.88	1831.32	242.16	371.93	456.40	112.69	850.04	48.21	48.99
1947	1007.11	1145.85	171.30	182.06	295.19	97.25	2777.18	373.55	568.91	654.97	187.60	1366.27	110.36	101.76
1948	789.57	898.78	151.99	153.36	240.23	89.63	2488.47	387.42	591.17	669.06	218.91	1454.97	112.85	95.41
1949	847.38	988.77	146.09	171.20	259.18	108.31	2266.56	349.87	562.02	592.63	187.88	1295.83	130.97	104.72
1950	679.63	824.37	108.06	158.51	194.54	70.00	1810.28	261.24	401.21	517.90	151.55	977.46	55.06	63.45
1951	1051.02	1184.87	140.74	188.25	261.82	102.90	2090.26	300.68	463.77	574.60	153.15	1083.94	91.08	67.35
1952	972.44	1164.23	187.50	192.30	284.64	123.11	3045.42	466.85	778.99	879.92	268.12	1874.68	161.78	131.00
1953	744.67	883.46	111.51	147.93	212.46	99.23	1868.67	287.46	464.65	475.36	82.38	1000.12	117.86	107.21
1954	340.53	406.60	48.77	75.41	113.46	42.56	968.70	209.69	318.18	276.42	117.02	549.98	29.41	55.67
1955	492.35	592.03	94.67	115.92	171.63	66.29	1487.11	249.92	372.09	399.65	91.53	797.95	42.97	76.91
1956	753.20	898.64	118.91	158.62	199.63	91.55	1725.41	305.33	459.60	492.50	152.71	1021.19	72.53	76.05
1957	1046.28	1233.56	206.67	233.32	354.67	172.16	3812.55	589.23	999.55	1051.31	398.44	2421.41	209.08	162.85
1958	705.37	848.10	156.58	137.47	211.06	89.96	1973.10	275.53	561.10	611.32	186.40	1233.51	135.40	103.21
1959	617.20	743.62	118.88	130.26	203.00	75.55	1993.25	220.34	324.16	361.54	104.17	715.27	59.03	72.53
1960	647.29	771.17	126.52	139.80	202.69	90.29	1771.79	310.01	475.38	423.15	125.97	944.26	92.17	77.19
1961	489.88	591.31	79.11	98.25	151.59	57.94	1320.01	218.30	336.60	345.45	92.44	684.63	69.14	54.38
1962	808.98	997.67	202.09	169.55	265.87	112.78	2692.93	437.68	728.61	747.02	215.08	1694.99	118.03	106.33
1963	363.95	459.21	61.41	111.42	136.12	61.60	1123.25	202.44	285.55	307.42	62.05	630.30	48.55	44.00
1964	430.63	354.04	97.06	123.74	192.14	71.12	1994.92	232.22	370.13	415.33	99.95	858.04	91.40	66.98
1965	981.95	605.49	188.51	211.24	298.97	125.11	2797.98	463.23	769.46	684.62	251.77	1925.98	143.61	131.48
1966	332.45	410.32	86.49	81.82	149.03	55.27	1390.09	243.24	376.24	383.67	97.05	782.29	53.50	59.98
1967	455.68	467.94	114.30	48.23	188.83	75.57	1736.02	285.94	432.59	519.56	116.15	996.10	36.49	61.74

TABLE 11 - S-4 SERIES (CFS)

	Station Numbers					
CSU	1278800	1278050	1272445	1077090	1073480	1073436
USGS	9.1650	9.1665	9.1725	9.3440	9.3575	9.3615
Year						
1938	376.81	1562.90	575.39	325.62	327.16	2336.76
1939	38.04	606.58	425.55	182.92	209.50	1098.61
1940	84.90	745.99	298.12	164.90	197.06	1028.62
1941	622.30	1851.80	1088.38	478.13	336.10	3077.72
1942	318.67	1715.27	530.48	358.20	304.86	2250.25
1943	449.01	1137.48	422.13	213.89	224.83	1595.65
1944	424.04	1639.32	759.53	311.61	308.98	2621.76
1945	340.66	1162.65	509.43	289.46	232.80	1706.87
1946	110.87	714.89	408.29	127.24	215.96	1217.53
1947	329.00	1042.36	517.55	176.18	291.08	1815.22
1948	358.02	1347.34	726.76	260.75	337.26	2426.52
1949	456.36	1380.07	658.53	290.30	340.17	2677.44
1950	92.95	793.92	354.92	148.56	180.38	1206.87
1951	205.16	462.49	260.02	127.78	165.28	928.70
1952	565.69	1859.43	697.05	380.26	365.02	2825.00
1953	241.09	647.71	397.84	169.55	180.92	1152.80
1954	194.39	494.48	258.19	144.24	162.09	1055.70
1955	232.12	638.44	349.38	149.37	164.89	1118.89
1956	248.65	668.54	347.71	161.12	205.02	1146.48
1957	568.05	1769.26	765.01	379.73	363.13	2551.41
1958	506.66	1494.09	888.34	310.33	285.13	2401.89
1959	143.14	352.93	282.65	123.73	176.30	861.30
1960	337.76	1020.05	516.91	253.53	248.82	1735.15
1961	265.36	770.40	482.98	187.66	208.59	1372.06
1962	361.31	1059.16	511.90	246.10	273.25	1855.92
1963	190.51	522.34	270.80	129.95	165.65	957.57
1964	230.50	630.49	398.27	142.47	175.87	1013.54
1965	503.80	1387.75	669.28	325.56	323.32	2487.34
1966	269.78	852.00	364.29	219.23	216.47	1419.96
1967	185.41	510.44	285.76	170.36	165.16	973.56

TABLE 12 - S-6 SERIES (CFS)

	Station Numbers					
CSU	1278800	1278050	1272445	1077090	1073480	1073436
USGS	9.1650	9.1665	9.1725	9.3440	9.3575	9.3615
Year						
1938	264.70	1087.32	428.89	233.04	234.72	1679.61
1939	32.70	441.02	323.29	136.78	149.07	832.04
1940	64.40	535.57	232.45	126.39	138.39	760.03
1941	438.72	1294.88	799.02	344.08	247.28	2228.01
1942	228.85	1207.55	403.54	243.55	220.95	1618.76
1943	323.33	820.58	351.01	158.26	172.19	1237.58
1944	298.37	1142.23	555.73	221.03	222.45	1864.03
1945	383.68	826.26	402.87	208.82	171.12	1270.55
1946	85.90	524.96	320.06	97.90	154.90	913.27
1947	243.36	767.28	410.77	137.72	215.76	1396.48
1948	254.48	948.10	530.04	185.66	241.83	1749.94
1949	323.63	972.30	469.79	211.16	242.48	1905.66
1950	70.84	571.55	263.88	109.55	128.96	886.80
1951	145.79	336.17	201.96	96.09	134.88	707.76
1952	389.84	1288.06	520.53	272.82	264.68	2010.24
1953	173.03	479.38	304.84	126.15	151.97	869.32
1954	138.63	361.00	204.30	108.44	117.40	788.60
1955	172.42	483.31	270.27	114.10	121.39	857.79
1956	176.90	494.15	258.79	133.56	144.73	853.34
1957	422.62	1291.87	587.51	285.37	273.42	1959.02
1958	349.47	1046.41	628.61	221.47	203.19	1701.05
1959	111.50	268.50	225.53	95.02	129.51	671.83
1960	237.14	723.01	376.56	182.67	175.81	1265.88
1961	189.47	555.96	361.68	141.88	149.11	1024.97
1962	251.22	754.19	378.03	176.30	196.04	1348.15
1963	144.45	405.77	229.42	103.43	122.02	764.80
1964	172.04	474.99	305.47	114.14	127.19	777.66
1965	367.10	1007.67	517.49	234.53	241.37	1863.86
1966	194.47	633.63	277.44	163.20	154.73	1080.99
1967	143.22	406.01	235.85	140.37	121.59	771.36

TABLE 13 - CS-4 SERIES (CFS)

				Station Numbers					
CSU	1425625	1377280	1377230	1377200	1373900	1373055	1373020	1371815	1370300
USGS	9.0975	9.1155	9.1180	9.1190	9.1275	9.1325	9.1345	9.1430	9.1520
Year						-			
1938	211.98	142.26	147.15	405.19	114.53	1642.21	205.27	90.56	111.74
1939	74.54	111.77	82.95	262.73	72.35	894.18	100.73	63.04	67.78
1940	65.77	55.15	48.25	89.25	105.32	841.89	98.93	75.51	97.24
1941	182.76	157.12	129.47	416.78	86.48	1385.74	175.09	132.19	148.55
1942	289.53	211.14	193.06	647.95	152.50	1579.42	172.69	123.79	143.21
1943	73.88	148.61	142.62	363.90	75.68	1059.44	111.46	75.26	60.63
1944	185.98	147.20	90.74	412.16	120.69	1480.44	159.55	116.49	132.25
1945	130.83	112.58	88.16	261.20	32.12	1249.94	126.28	101.08	87.00
1946	92.40	60.34	61.08	124.30	60.75	847.02	67.73	55.91	56.20
1947	130.23	147.52	136.91	401.64	75.77	1194.08	136.04	115.53	81.28
1948	170.25	153.99	128.68	485.11	115.13	1392.71	118.72	97.64	92.22
1949	134.23	177.18	139.83	582.28	86.42	1239.87	142.84	95.66	96.21
1950	80.85	73.22	84.37	189.60	57.45	1222.23	119.98	84.06	53.78
1951	42.20	120.06	86.09	339.52	48.28	900.74	83.58	62.22	44.54
1952	181.21	223.94	178.77	636.87	120.89	1760.47	195.21	166.94	112.23
1953	74.08	160.10	143.88	330.64	77.19	857.61	74.72	64.32	36.70
1954	34.92	35.35	69.57	68.52	21.66	445.60	70.88	57.12	43.29
1955	59.96	53.48	100.22	114.93	39.45	819.78	103.11	85.36	61.89
1956	47.87	98.03	101.35	227.28	51.96	868.61	38.79	61.85	42.92
1957	221.73	278.21	216.48	800.97	147.08	2200.99	259.23	128.75	128.55
1958	185.21	189.82	141.25	496.77	139.64	1297.41	116.86	132.44	125.35
1959	45.48	74.47	93.10	130.29	66.34	660.52	129.36	52.46	42.69
1960	86.97	122.16	103.95	271.42	45.57	882.82	172.63	71.83	66.45
1961	55.26	90.66	68.80	150.39	46.02	651.57	66.94	69.35	43.75
1962	190.55	163.82	148.87	407.72	95.54	1651.73	161.40	111.98	76.97
1963	23.34	57.07	53.86	107.67	30.68	558.43	66.95	49.42	19.60
1964	106.35	123.24	86.33	270.83	77.64	989.99	95.81	61.17	49.85
1965	142.90	193.54	168.81	524.61	112.12	1373.51	131.16	97.77	82.81
1966	62.55	66.46	74.56	156.68	56.62	739.28	85.61	84.05	45.48
1967	41.83	44.29	78.78	104.93	30.83	829.28	105.95	71.72	28.71

TABLE 14 - CS-6 SERIES (CFS)

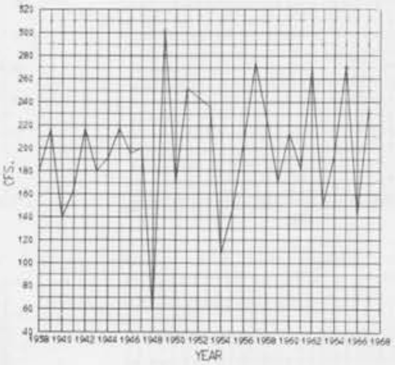
				Station Numbers					
CSU	1425625	1377280	1377230	1377200	1373900	1373055	1373020	1371815	1370300
USGS	9.0975	9.1155	9.1180	9.1100	9.1275	9.1325	9.1345	9.1430	9.1520
Year									
1938	144.14	103.19	108.20	302.53	78.66	1136.71	142.02	60.48	80.24
1939	33.13	82.40	71.45	238.90	52.07	636.67	70.95	50.37	49.77
1940	46.75	43.81	39.15	91.55	72.57	592.48	69.85	56.37	69.68
1941	123.01	113.88	96.58	326.14	60.46	969.91	122.12	97.97	105.32
1942	194.33	130.62	140.25	474.42	105.08	1090.52	119.28	92.60	101.63
1943	54.77	109.85	108.00	291.91	53.81	758.22	78.86	59.76	45.54
1944	124.48	106.73	68.86	308.07	81.75	1018.14	97.68	89.57	96.05
1945	90.12	85.38	72.17	229.69	24.91	884.45	90.13	80.43	64.59
1946	64.12	48.21	48.90	123.36	45.47	600.70	49.37	45.81	42.73
1947	92.85	110.36	101.76	320.93	53.40	846.48	96.35	85.87	60.44
1948	115.45	112.35	95.41	363.62	79.24	966.05	84.57	75.55	66.79
1949	90.92	130.97	104.72	435.31	60.49	860.50	101.60	75.59	71.48
1950	55.82	55.06	63.45	152.94	40.53	843.82	86.45	67.46	40.53
1951	29.41	91.08	67.35	196.48	34.44	634.29	61.60	50.05	34.28
1952	122.63	161.78	131.00	468.72	82.59	1220.74	136.59	122.21	80.63
1953	51.38	117.86	107.21	271.75	54.44	613.11	55.97	50.46	42.77
1954	24.46	29.41	55.67	71.27	15.99	323.08	52.32	45.07	33.25
1955	40.93	42.97	76.91	109.68	28.76	584.86	74.74	66.55	47.04
1956	33.63	72.53	76.05	174.49	37.67	615.69	64.30	48.27	33.49
1957	149.42	209.08	162.35	619.51	100.67	1553.36	181.89	100.35	92.67
1958	126.36	135.40	103.21	363.15	94.29	900.00	82.06	99.83	90.44
1959	31.24	59.03	72.53	123.33	46.51	468.01	91.14	42.57	33.60
1960	60.31	92.17	77.19	219.38	33.19	623.26	120.63	57.48	49.85
1961	37.06	60.14	54.58	133.32	32.17	460.72	50.14	47.68	30.89
1962	129.10	118.05	108.33	304.76	65.28	1146.48	114.67	85.67	54.38
1963	20.40	48.55	44.90	114.68	25.22	405.58	48.99	38.41	13.95
1964	72.26	91.40	66.98	217.55	53.85	693.73	68.87	49.22	35.18
1965	96.84	145.61	131.49	419.56	77.91	1102.29	94.71	76.68	59.73
1966	46.73	53.50	59.98	143.56	41.21	538.26	62.46	65.36	32.40
1967	31.96	36.49	61.74	101.06	23.33	615.83	76.43	58.01	21.54

TABLE 15 - STATIONS WITH MISSING DATA

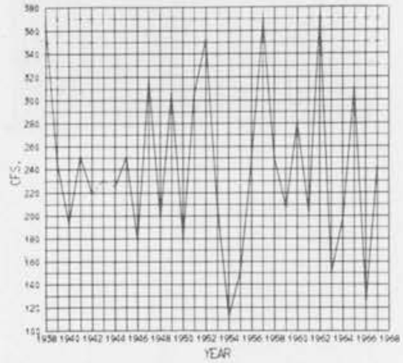
Station with missing data		Filling in of missing data is made with station		Year of missing data
CSU Sta. No.	USGS Sta. No.	CSU Sta. No.	USGS Sta. No.	
1820000	9.0195	1830000	9.0190	54-60
1830000	9.0190	1960000	9.0110	38-50
1970000	9.0105	1960000	9.0110	38-53
1272445	9.1725	1277200	9.1665	38-42
1278800	9.1650	1277200	9.1665	38-51
1371815	9.1430	1370300	9.1520	38-39
1373020	9.1345	1373055	9.1325	57-60
1373900	9.1275	1373360	9.1285	38-45; 55-60
1377230	9.1180	1377280	9.1155	51-60
1377825	9.1135	1378100	9.1125	38-40; 51-58
1594236	9.0785	1378400	9.1100	38-47
1720000	9.0595	1590000	9.0850	38-44
1377500	9.1145	1378400	9.1100	38-44
1379000	9.1090	1378400	9.1100	38
1594260	9.0780	1378400	9.1100	38-47

Fig. 5 N-4 series

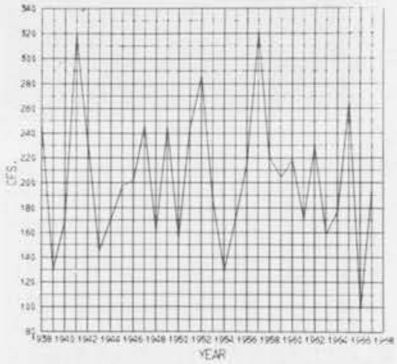
N-4 CSU STA. 1970000 USGS STA. 9.0105



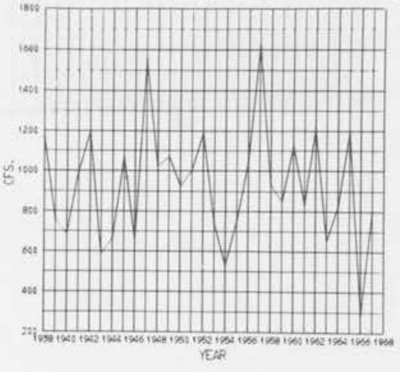
N-4 CSU STA. 1960000 USGS STA. 9.0110



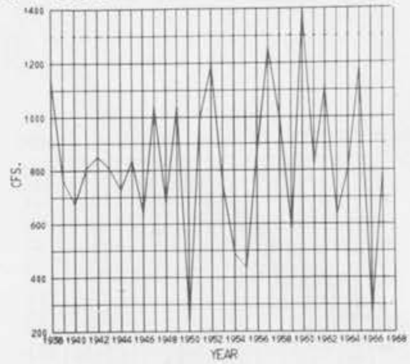
N-4 CSU STA. 1866000 USGS STA. 9.0165



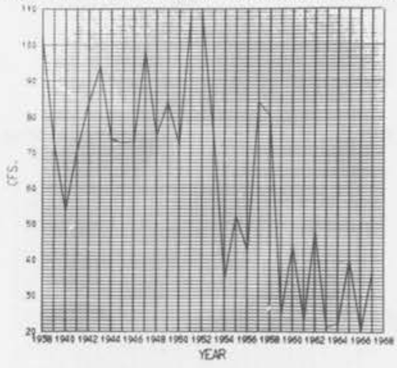
N-4 CSU STA. 1830000 USGS STA. 9.0190



N-4 CSU STA. 1820000 USGS STA. 9.0195



N-4 CSU STA. 1802730 USGS STA. 9.0265



N-4 CSU STA. 1776000 USGS STA. 9.0360

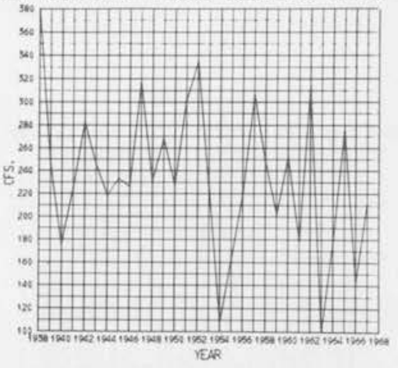
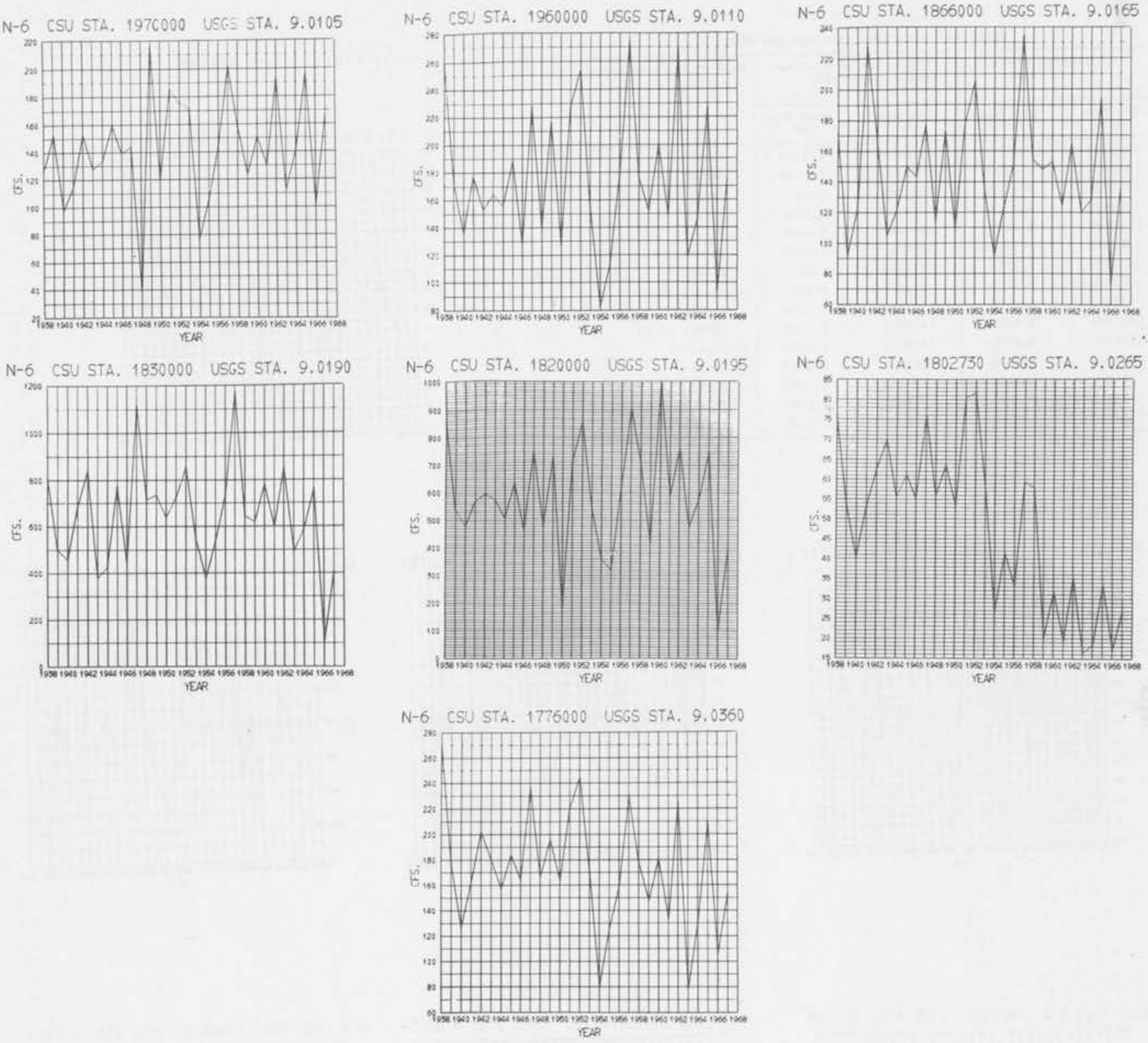


Fig. 6 N-6 series



N-6 CSU STA. 1970000 USGS STA. 9.0105

N-6 CSU STA. 1960000 USGS STA. 9.0110

N-6 CSU STA. 1866000 USGS STA. 9.0165

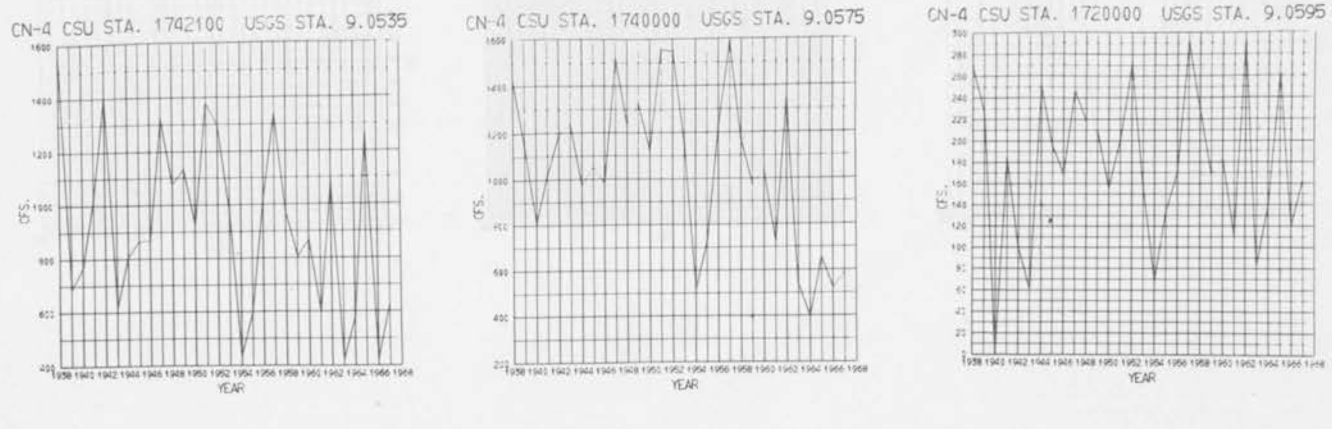
N-6 CSU STA. 1830000 USGS STA. 9.0190

N-6 CSU STA. 1820000 USGS STA. 9.0195

N-6 CSU STA. 1802730 USGS STA. 9.0265

N-6 CSU STA. 1776000 USGS STA. 9.0360

Fig. 7 CN-4 series

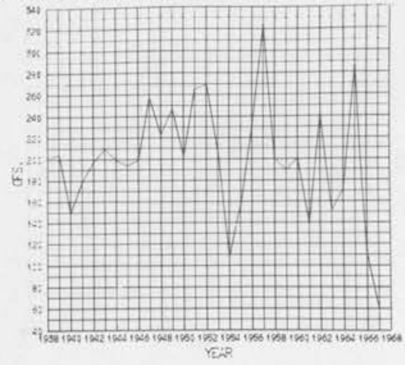


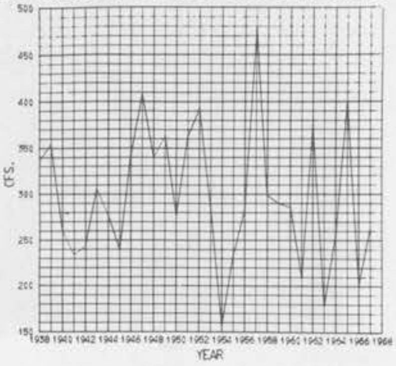
CN-4 CSU STA. 1742100 USGS STA. 9.0535

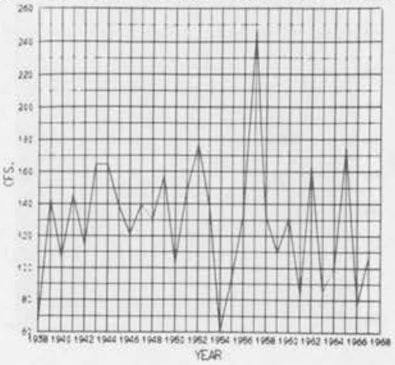
CN-4 CSU STA. 1740000 USGS STA. 9.0575

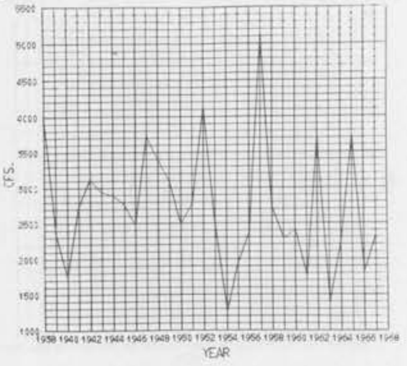
CN-4 CSU STA. 1720000 USGS STA. 9.0595

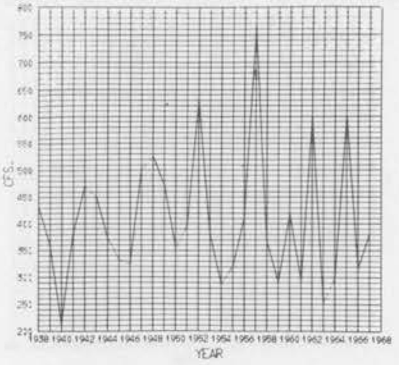
Fig. 7 CN-4 series - Continued

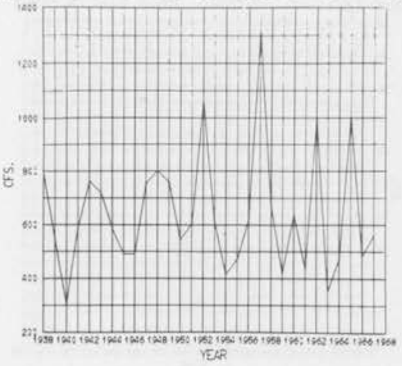

CN-4 CSU STA. 1666300 USGS STA. 9.0645

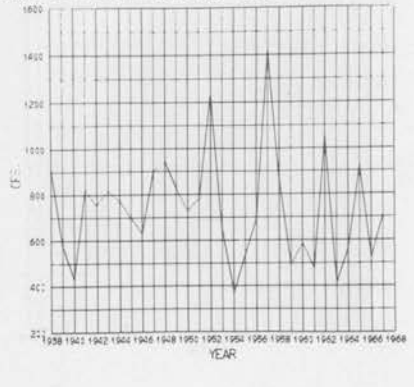

CN-4 CSU STA. 1594260 USGS STA. 9.0780

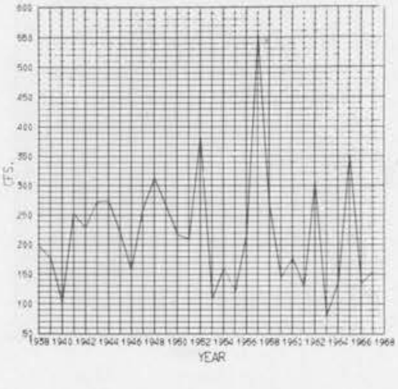

CN-4 CSU STA. 1594236 USGS STA. 9.0785

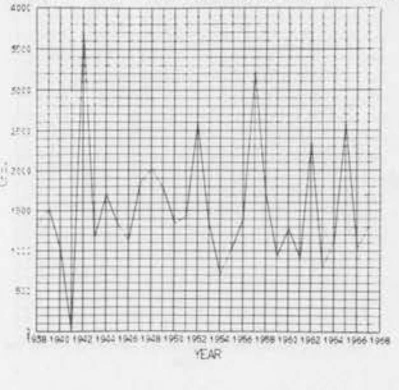

CN-4 CSU STA. 1590000 USGS STA. 9.0850

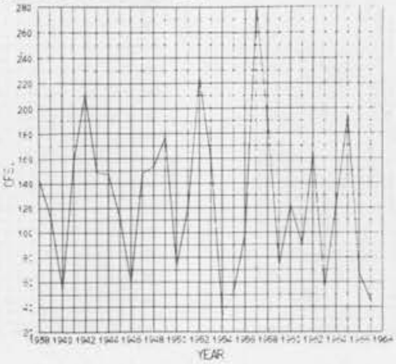

CN-4 CSU STA. 1379000 USGS STA. 9.1090


CN-4 CSU STA. 1378400 USGS STA. 9.1100


CN-4 CSU STA. 1378100 USGS STA. 9.1125


CN-4 CSU STA. 1377825 USGS STA. 9.1135


CN-4 CSU STA. 1377500 USGS STA. 9.1145


CN-4 CSU STA. 1377280 USGS STA. 9.1155

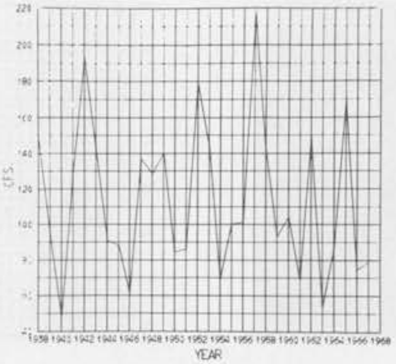
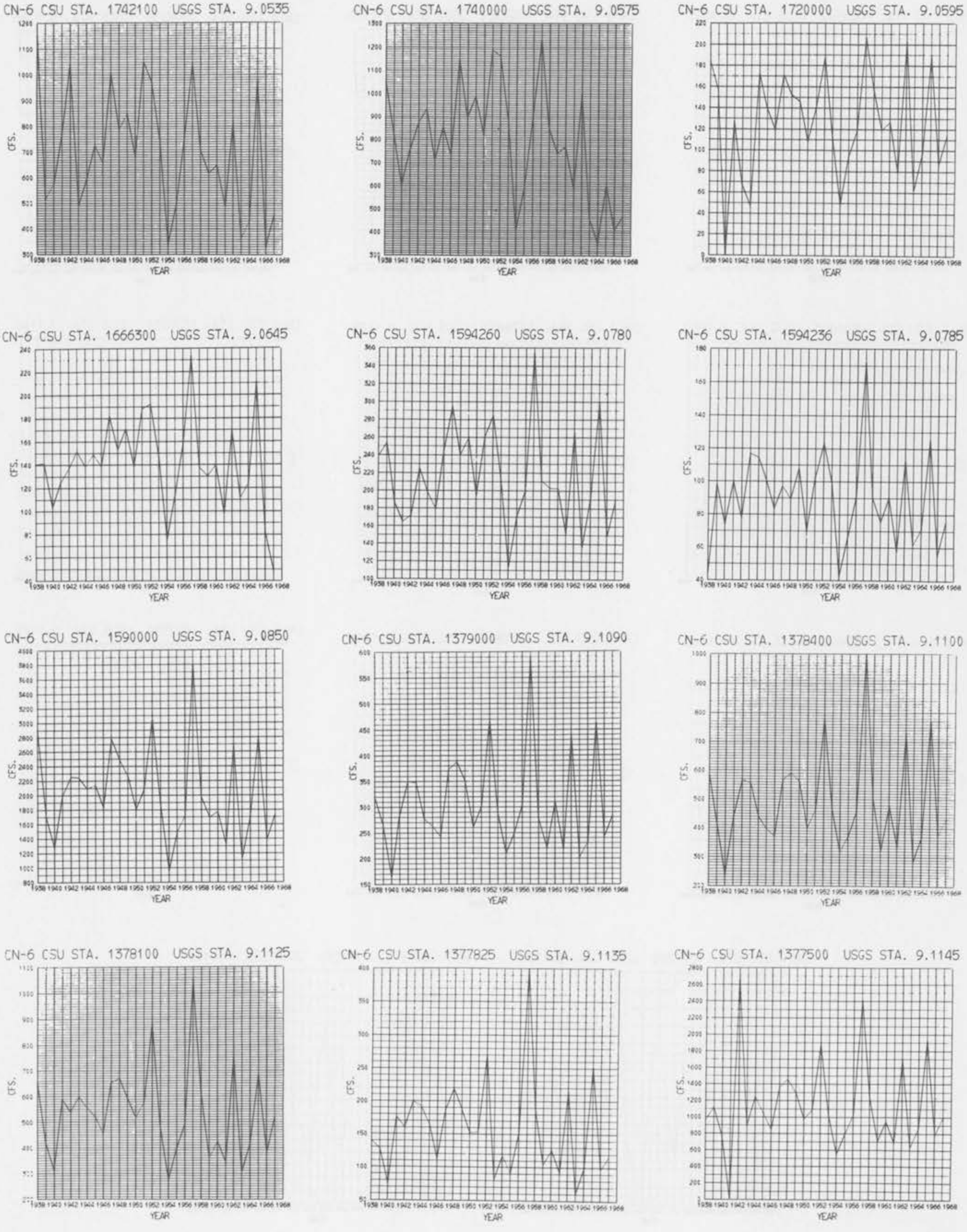

CN-4 CSU STA. 1377230 USGS STA. 9.1180

Fig. 8 CN-6 series



CN-6 CSU STA. 1742100 USGS STA. 9.0535

CN-6 CSU STA. 1740000 USGS STA. 9.0575

CN-6 CSU STA. 1720000 USGS STA. 9.0595

CN-6 CSU STA. 1666300 USGS STA. 9.0645

CN-6 CSU STA. 1594260 USGS STA. 9.0780

CN-6 CSU STA. 1594236 USGS STA. 9.0785

CN-6 CSU STA. 1590000 USGS STA. 9.0850

CN-6 CSU STA. 1379000 USGS STA. 9.1090

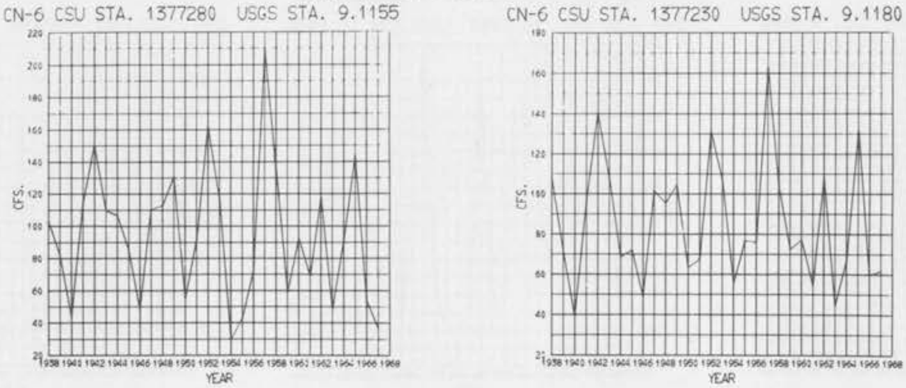
CN-6 CSU STA. 1378400 USGS STA. 9.1100

CN-6 CSU STA. 1378100 USGS STA. 9.1125

CN-6 CSU STA. 1377825 USGS STA. 9.1135

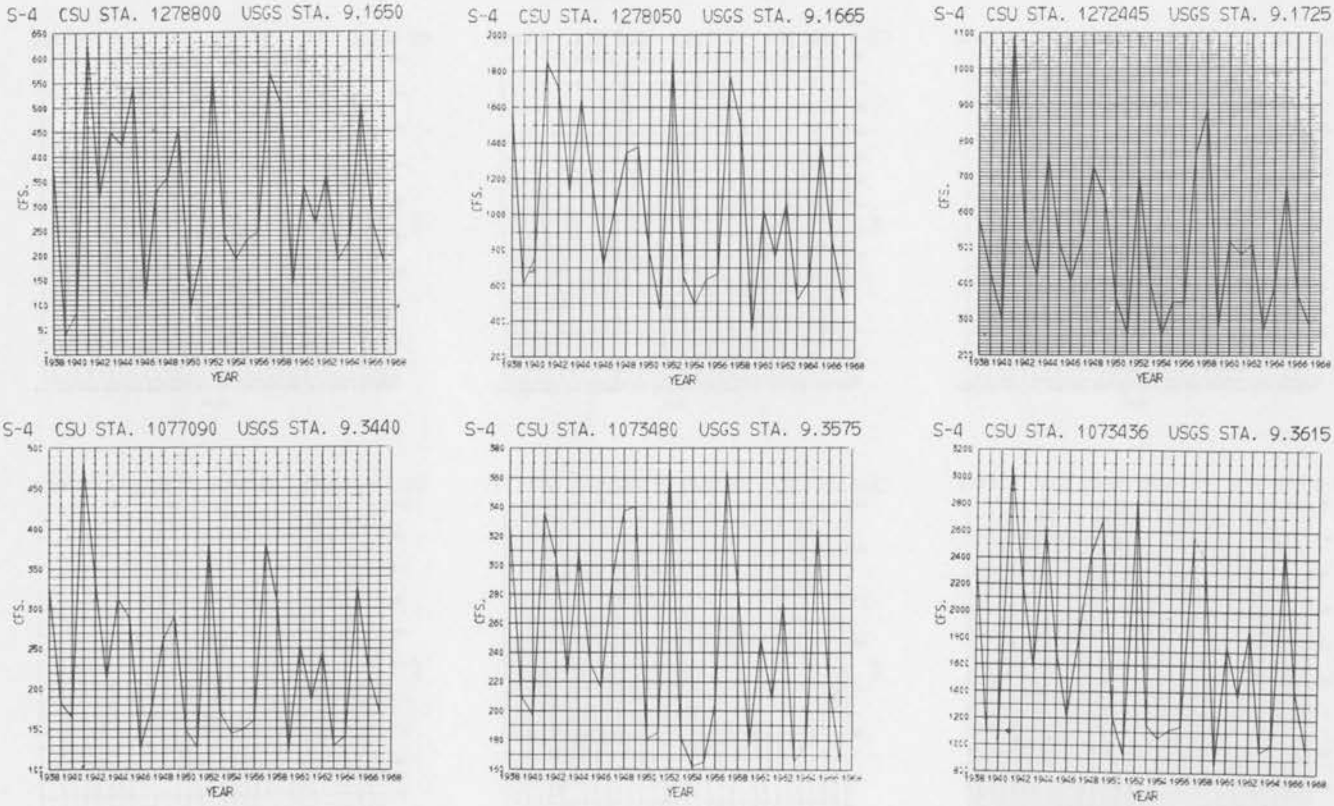
CN-6 CSU STA. 1377500 USGS STA. 9.1145

Fig. 8 CN-6 series - Continued


CN-6 CSU STA. 1377280 USGS STA. 9.1155

CN-6 CSU STA. 1377230 USGS STA. 9.1180

Fig. 9 S-4 series


S-4 CSU STA. 1278800 USGS STA. 9.1650

S-4 CSU STA. 1278050 USGS STA. 9.1665

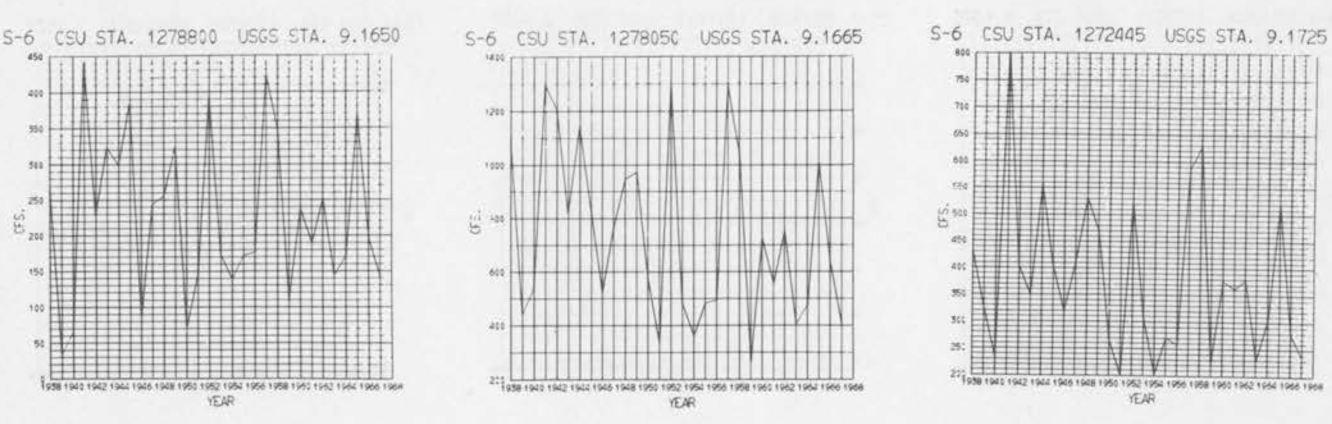
S-4 CSU STA. 1272445 USGS STA. 9.1725

S-4 CSU STA. 1077090 USGS STA. 9.3440

S-4 CSU STA. 1073480 USGS STA. 9.3575

S-4 CSU STA. 1073436 USGS STA. 9.3615

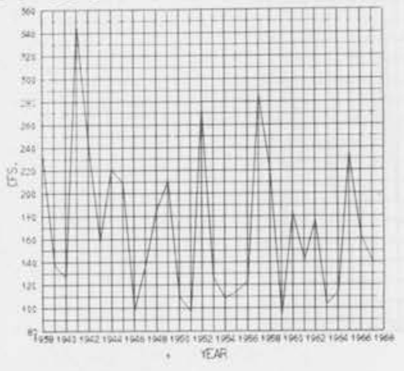
Fig. 10 S-6 series

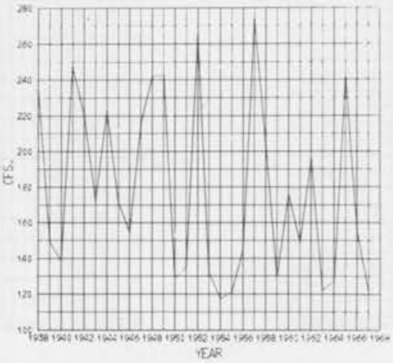

S-6 CSU STA. 1278800 USGS STA. 9.1650

S-6 CSU STA. 1278050 USGS STA. 9.1665

S-6 CSU STA. 1272445 USGS STA. 9.1725

Fig. 10 S-6 series - Continued


S-6 CSU STA. 1077090 USGS STA. 9.3440


S-6 CSU STA. 1073480 USGS STA. 9.3575

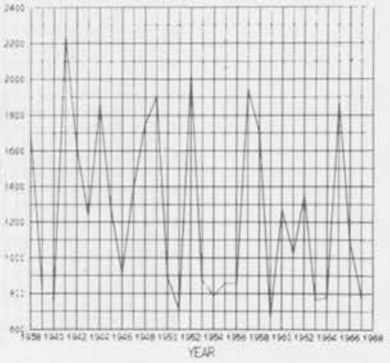
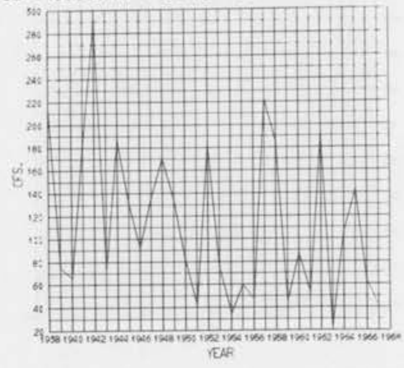
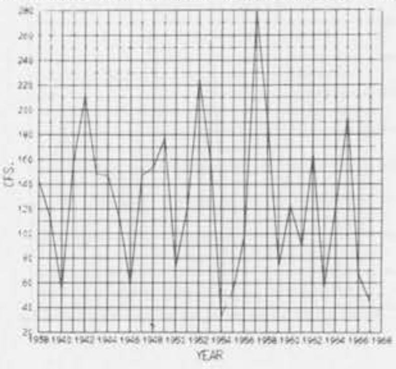
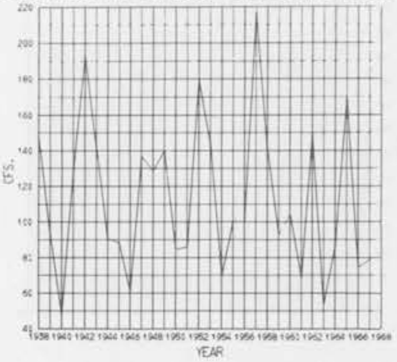
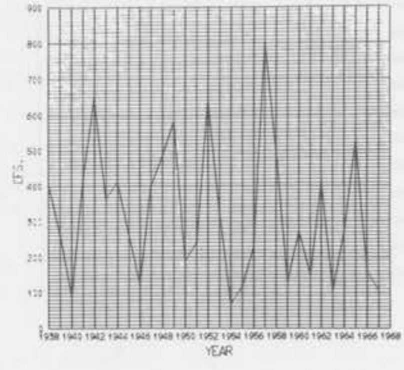

S-6 CSU STA. 1073436 USGS STA. 9.3615

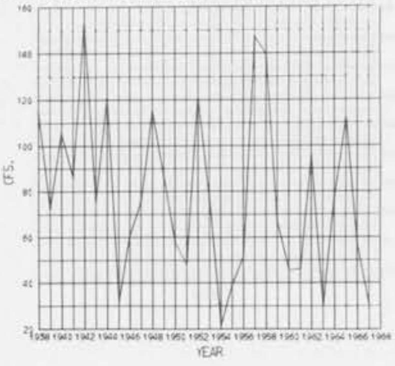
Fig. 11 CS-4 series

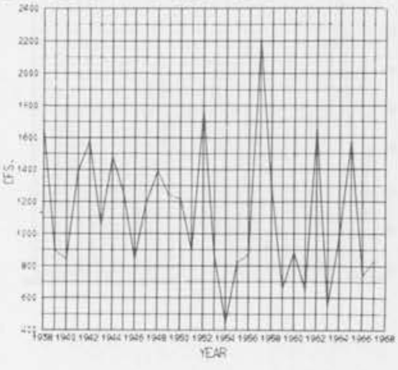

CS-4 CSU STA. 1425625 USGS STA. 9.0975

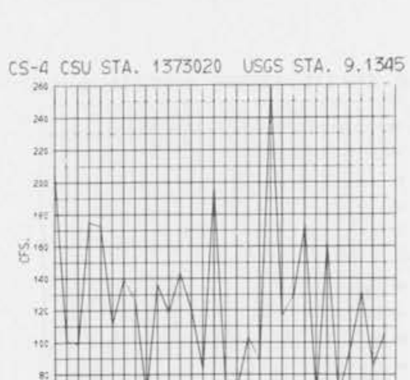

CS-4 CSU STA. 1377280 USGS STA. 9.1155


CS-4 CSU STA. 1377230 USGS STA. 9.1180


CS-4 CSU STA. 1377200 USGS STA. 9.1190


CS-4 CSU STA. 1373900 USGS STA. 9.1275


CS-4 CSU STA. 1373055 USGS STA. 9.1325


CS-4 CSU STA. 1373020 USGS STA. 9.1345


CS-4 CSU STA. 1371815 USGS STA. 9.1430

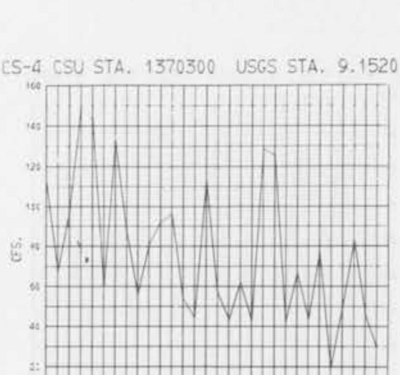
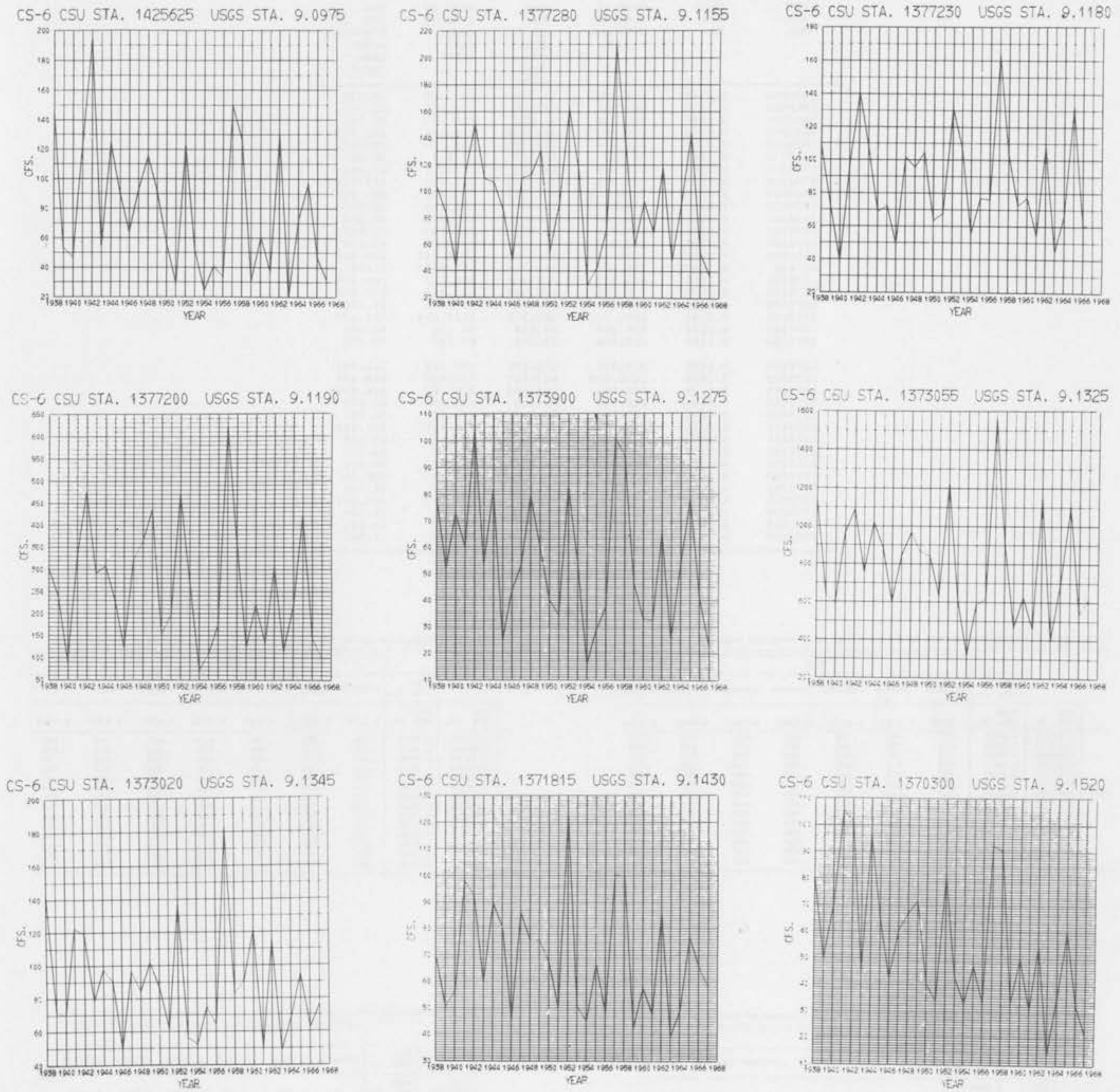

CS-4 CSU STA. 1370300 USGS STA. 9.1520

Fig. 12 CS-6 series


CS-6 CSU STA. 1425625 USGS STA. 9.0975

CS-6 CSU STA. 1377280 USGS STA. 9.1155

CS-6 CSU STA. 1377230 USGS STA. 9.1180

CS-6 CSU STA. 1377200 USGS STA. 9.1190

CS-6 CSU STA. 1373900 USGS STA. 9.1275

CS-6 CSU STA. 1373055 USGS STA. 9.1325

CS-6 CSU STA. 1373020 USGS STA. 9.1345

CS-6 CSU STA. 1371815 USGS STA. 9.1430

CS-6 CSU STA. 1370300 USGS STA. 9.1520

TABLE 16 - MEANS AND STANDARD DEVIATIONS OF 30 YEAR RAW DATA

CSU Sta. No.	USGS Sta. No.	Mean of 4-month averages (cfs)	Std. Dev. of 4-month averages (cfs)	Mean of 6-month averages (cfs)	Std. Dev. of 6-month averages (cfs)
1970000	9.0105	198.449	55.552	141.865	38.338
1960000	9.0110	241.821	71.196	174.569	51.065
1866000	9.0165	203.590	53.612	146.297	38.545
1830000	9.0190	931.757	290.050	644.206	220.359
1820000	9.0195	826.556	274.385	582.724	203.842
1802730	9.0265	63.007	27.307	47.814	20.085
1776000	9.0360	234.679	64.188	171.954	45.884
1742100	9.0535	924.237	316.280	702.783	233.361
1740000	9.0575	1043.263	341.708	794.292	241.819
1720000	9.0595	177.674	72.281	124.358	50.072
1666300	9.0645	199.184	55.142	141.030	39.140
1594260	9.0780	297.711	73.851	215.045	53.847
1594236	9.0785	128.576	38.515	89.611	27.138
1590000	9.0850	2739.444	854.102	2031.847	624.926
137900	9.1090	406.685	122.728	306.039	91.987
1378400	9.1100	641.932	224.886	486.119	165.435
1378100	9.1125	736.162	236.020	534.129	170.870
1377825	9.1135	219.301	98.861	157.011	69.485
1377500	9.1145	1521.405	754.366	1129.644	546.188
1377280	9.1155	126.388	59.684	94.178	42.221
1377230	9.1180	113.268	42.698	85.892	30.376
1278800	9.1650	314.930	159.674	226.413	111.344
1278050	9.1665	1028.025	467.197	738.323	319.454
1272445	9.1725	500.048	204.184	379.190	144.622
1077090	9.3440	230.964	93.315	170.480	64.553
1073480	9.3575	245.702	68.310	178.304	50.207
1073436	9.3615	1696.563	688.607	1254.713	481.412
1425625	9.0975	114.324	68.267	78.467	45.159
1377280	9.1155	126.388	59.684	94.178	42.221
1377230	9.1180	113.268	42.698	85.892	30.376
1377200	9.1190	322.737	192.349	257.047	136.341
1373900	9.1275	78.756	36.701	55.056	24.150
1373055	9.1325	1124.250	410.613	790.065	280.861
1373020	9.1345	124.166	46.158	88.247	31.349
1371815	9.1430	88.115	29.509	68.390	21.124
1370300	9.1520	76.695	35.297	56.029	24.863

TABLE 17 - CORRELATION MATRIX BETWEEN N-4 AND CN-4 (computed from 30-year data)

			N-4						
		CSU STA. NO.	1970000	1960000	1866000	1830000	1820000	1802730	1776000
	CSU STA. NO.	USGS STA. NO.	9.0105	9.0110	9.0165	9.0190	9.0195	9.0265	9.0360
CN-4	1742100	9.0535	.477	.785	.778	.815	.641	.710	.894
	1740000	9.0575	.411	.728	.566	.669	.531	.843	.836
	1720000	9.0595	.524	.771	.592	.660	.593	.421	.730
	1666300	9.0645	.535	.717	.640	.728	.619	.592	.721
	1594260	9.0780	.582	.802	.597	.702	.640	.585	.805
	1594236	9.0785	.621	.652	.602	.565	.584	.477	.549
	1590000	9.0850	.502	.845	.722	.806	.673	.641	.870
	1379000	9.1090	.517	.767	.655	.754	.662	.469	.730
	1378400	9.1100	.541	.789	.671	.743	.685	.489	.757
	1378100	9.1125	.497	.801	.714	.740	.621	.627	.791
	1377825	9.1135	.426	.680	.639	.686	.564	.498	.627
	1377500	9.1145	.497	.533	.419	.632	.491	.395	.602
	1377280	9.1155	.553	.710	.692	.694	.694	.567	.708
	1377230	9.1180	.490	.674	.674	.704	.612	.537	.719

TABLE 18 - CORRELATION MATRIX BETWEEN N-6 AND CN-6 (computed from 30-year data)

			N-6						
		CSU STA. NO.	1970000	1960000	1866000	1830000	1820000	1802730	1776000
	CSU STA. NO.	USGS STA. NO.	9.0105	9.0110	9.0165	9.0190	9.0195	9.0265	9.0360
CN-6	1742100	9.0535	.486	.783	.780	.813	.671	.706	.896
	1740000	9.0575	.457	.756	.598	.731	.631	.825	.855
	1720000	9.0595	.529	.770	.587	.620	.569	.408	.736
	1666300	9.0645	.570	.740	.659	.750	.668	.578	.745
	1594260	9.0780	.598	.798	.592	.659	.621	.555	.803
	1594236	9.0785	.627	.650	.603	.529	.552	.448	.562
	1590000	9.0850	.509	.840	.720	.764	.659	.623	.876
	1379000	9.1090	.529	.766	.658	.704	.613	.438	.734
	1378400	9.1100	.551	.788	.669	.693	.639	.456	.761
	1378100	9.1125	.507	.802	.716	.700	.597	.599	.799
	1377825	9.1135	.433	.681	.640	.650	.541	.477	.644
	1377500	9.1145	.503	.532	.420	.596	.450	.373	.604
	1377280	9.1155	.555	.708	.701	.689	.695	.542	.715
	1377230	9.1180	.497	.668	.673	.674	.593	.509	.723

TABLE 19 - CORRELATION MATRIX BETWEEN S-4 AND CS-4 (computed from 30-year data)

			S-4					
		CSU STA. NO.	1278800	1278050	1272445	1077090	1073480	1073436
	CSU STA. NO.	USGS STA. NO.	9.1650	9.1665	9.1725	9.3440	9.3575	9.3615
CS-4	1425625	9.0975	.656	.890	.752	.811	.849	.830
	1377280	9.1155	.748	.807	.718	.753	.830	.782
	1377230	9.1180	.682	.742	.593	.695	.760	.709
	1377200	9.1190	.748	.859	.737	.786	.889	.842
	1373900	9.1275	.491	.776	.661	.663	.770	.714
	1373055	9.1325	.707	.861	.711	.792	.858	.810
	1373020	9.1345	.643	.776	.612	.773	.777	.723
	1371815	9.1430	.772	.884	.784	.836	.819	.850
	1370300	9.1520	.675	.908	.835	.866	.828	.856

TABLE 20 - CORRELATION MATRIX BETWEEN S-6 AND CS-6 (computed from 30-year data)

			S-6					
		CSU STA. NO.	1278800	1278050	1272445	1077090	1073480	1073436
	CSU STA. NO.	USGS STA. NO.	9.1650	9.1665	9.1725	9.3440	9.3575	9.3615
CS-6	1425625	9.0975	.653	.892	.754	.804	.846	.826
	1377280	9.1155	.753	.805	.722	.747	.840	.786
	1377230	9.1180	.702	.747	.608	.699	.779	.722
	1377200	9.1190	.753	.854	.746	.783	.894	.841
	1373900	9.1275	.492	.778	.659	.660	.770	.712
	1373055	9.1325	.716	.863	.720	.791	.866	.813
	1373020	9.1345	.656	.779	.624	.780	.787	.733
	1371815	9.1430	.777	.888	.793	.837	.828	.854
	1370300	9.1520	.666	.896	.829	.848	.821	.845

Chapter V

DATA ANALYSIS AND RESULTS

In this chapter the data described in Chapter IV are analyzed according to the procedures discussed in Chapter III. The approaches used for reducing the number of runoff variables are the principal component analysis and the canonical analysis. The minimum numbers of years to detect the increase in the runoff means are obtained by application of equation (1).

In the principal component analysis and the canonical analysis, the coefficients for the principal components and the canonical variables are obtained basically from the analysis of the covariance matrix. Therefore, because the covariance matrix is assumed to be the same for both periods, it follows that the coefficients obtained for the non-seeded period apply for the seeded period as well. The suspected change in the means of the runoff leave the coefficients of the components invariant.

5.1 The application of principal component analysis. The numerical procedures for the reduction of the number of runoff variables by the principal components method were executed separately in each region on the CDC 6400 digital computer of Colorado State University. The program BMD01M from the University of California Press was modified to accommodate nonstandardized variables. The zero mean is not desirable here because a certain percent increase in the mean will be postulated later.

The steps in obtaining the principal components in each region may be summarized as follows:

1) Compute the covariance matrix of the runoff variables in that region, $\underline{\hat{V}}$, as defined in equation (2).

2) Solve the system,

$$|\underline{\hat{V}} - \lambda I| = 0 \quad , \tag{21}$$

to obtain $\lambda_1, \lambda_2, \ldots, \lambda_p$, the characteristic roots, which are the amounts of variances of components 1, 2, ..., p .

3) Solve the system,

$$(\underline{\hat{V}} - \lambda_i \ I)\underline{\beta}_i = \underline{0} \tag{22}$$

subject to the normalization condition,

$$\underline{\beta}_i' \ \underline{\beta}_i = 1 \tag{23}$$

to obtain $\underline{\beta}_i$ which is the vector of the coefficients for the i^{th} component in that region.

For example, when N-4, which is the four-month runoff of the northern region, is used the coefficients for the first principal component are found to be (Table 21),

$$\beta_{1,1} = 0.0859$$

$$\beta_{1,2} = 0.1679$$

$$\beta_{1,3} = 0.1151$$

$$\beta_{1,4} = 0.7065$$

$$\beta_{1,5} = 0.6576$$

$$\beta_{1,6} = 0.0332$$

$$\beta_{1,7} = 0.1359$$

where the first subscript of β indicates the ordering number of the principal component, the second one indicates the sequential number of the station as shown in Table 2.

Let ξ_i be the i^{th} principal component in the target region before seeding, then for N-4,

$$\xi_1 = \sum_{j=1}^{7} \beta_{1,j} \ Q_j$$

$$= 0.0859Q_1 + 0.1679Q_2 + 0.1151Q_3 + 0.7065Q_4$$

$$+ 0.6576Q_5 + 0.0332Q_6 + 0.1359Q_7$$

where Q_1, Q_2, Q_3, Q_4, Q_5, Q_6 and Q_7 are runoff variables listed in order corresponding to the numbers in the 'Seq. No.' column in Table 2. This first principal component will account for the largest percentage of the total variation in this whole region based on the four-month spring runoff.

The coefficients for the principal components in N-4, N-6, CN-4, CN-6, S-4, S-6, CS-4 and CS-6 are shown in Tables 21, 22, 23, 24, 25, 26, 27, and 28, respectively. The cumulative percentages of total variation accounted for by the principal components in each region are shown in Table 29. A 99 cumulative percentage was used to limit the number of the principal components to be retained for the study, because it was found that beyond this percentage of total variation, the rate of increase of the cumulative percentage was very slow.

After the coefficients of the principal components in each region have been found, then the series of the principal components can be simply obtained from the original series [12].

TABLE 21 - COEFFICIENTS FOR THE PRINCIPAL COMPONENTS OF N-4

CSU Sta. No.	USGS Sta. No.	1st Comp.	2nd Comp.	3rd Comp.	4th Comp.
1970000	9.0105	.0859	-.0894	-.4339	-.8081
1960000	9.0110	.1679	-.0529	-.4719	.0637
1866000	9.0165	.1151	.0334	-.1221	-.2757
1830000	9.0190	.7065	.6848	.1407	-.0308
1820000	9.0195	.6576	-.7201	.1966	.0688
1802730	9.0265	.0332	.0191	-.3072	.2822
1776000	9.0360	.1359	.0132	-.6491	.4262

TABLE 22 - COEFFICIENTS FOR THE PRINCIPAL COMPONENTS OF N-6

CSU Sta. No.	USGS Sta. No.	1st Comp.	2nd Comp.	3rd Comp.	4th Comp.
1970000	9.0105	.0767	-.0806	-.5604	-.6494
1960000	9.0110	.1549	-.0680	-.5037	.0808
1866000	9.0165	.1084	.0256	-.2105	-.2926
1830000	9.0190	.7191	.6784	.1135	-.0377
1820000	9.0195	.6510	-.7266	.2122	.0154
1802730	9.0265	.0339	.0048	-.1892	.4046
1776000	9.0360	.1279	-.0079	-.5424	.5664

TABLE 23 - COEFFICIENTS FOR THE PRINCIPAL COMPONENTS OF CN-4

CSU Sta. No.	USGS Sta. No.	1st Comp.	2nd Comp.	3rd Comp.	4th Comp.
1742100	9.0535	.2250	-.1496	-.4782	-.7580
1740000	9.0575	.2155	-.2714	-.7505	.5419
1720000	9.0599	.0444	-.0508	.0329	-.0134
1666300	9.0645	.0378	-.0229	-.0434	.0232
1594260	9.0780	.0524	-.0388	-.0108	.0455
1594236	9.0785	.0240	-.0114	.0178	.0891
1590000	9.0850	.7025	-.4654	.3580	-.0949
1379000	9.1090	.0971	-.0158	.0912	.1170
1378400	9.1100	.1803	-.0355	.1781	.1584
1378100	9.1125	.1862	-.1309	.1338	.2226
1377825	9.1135	.0733	-.0277	.0926	.1475
1377500	9.1145	.5637	.8144	-.0985	.0404
1377280	9.1155	.0444	-.0050	.0128	.0178
1377230	9.1180	.0320	-.0011	.0114	.0005

TABLE 24 - COEFFICIENTS FOR THE PRINCIPAL COMPONENTS OF CN-6

CSU Sta. No.	USGS Sta. No.	1st Comp.	2nd Comp.	3rd Comp.	4th Comp.
1742100	9.0535	.2268	-.1513	-.5634	-.7013
1740000	9.0575	.2156	-.2566	-.6879	.6239
1720000	9.0595	.0422	-.0478	.0304	-.0128
166300	9.0645	.0375	-.0220	-.0413	.0318
1594260	9.0780	.0528	-.0362	-.0035	.0583
1594236	9.0785	.0233	-.0100	.0220	.0898
1590000	9.0850	.7062	-.4663	.3442	-.1245
1379000	9.1090	.1005	-.0147	.1038	.1050
1378400	9.1100	.1825	-.0337	.1947	.1356
1378100	9.1125	.1858	-.1261	.1495	.2038
1377825	9.1135	.0710	-.0262	.0944	.1331
1377500	9.1145	.5577	.8196	-.0869	.0420
1377280	9.1155	.0433	-.0047	.0120	.0192
1377230	9.1180	.0313	-.0008	.0125	-.0051

TABLE 25 - COEFFICIENTS FOR THE PRINCIPAL COMPONENTS OF S-4

CSU Sta. No.	USGS Sta. No.	1st Comp.	2nd Comp.	3rd Comp.
1278800	9.1650	-.1608	-.0738	-.8889
1278050	9.1665	-.5304	.8066	-.0525
1272445	9.1725	-.2180	-.4039	-.2817
1077090	9.3440	-.1027	.0634	-.1532
1073480	9.3575	-.0754	-.0045	.1153
1073436	9.3615	-.7931	-.4205	.3017

TABLE 26 - COEFFICIENTS FOR THE PRINCIPAL COMPONENTS OF S-6

CSU Sta. No.	USGS Sta. No.	1st Comp.	2nd Comp.	3rd Comp.
1278800	9.1650	-.1622	-.1421	-.8496
1278050	9.1665	-.5207	.8186	-.1102
1272445	9.1725	-.2240	-.3730	-.3252
1077090	9.3440	-.1013	.0618	-.1660
1073480	9.3575	-.0802	-.0038	.1155
1073436	9.3615	-.7973	-.4084	.3456

TABLE 27 - COEFFICIENTS FOR THE PRINCIPAL COMPONENTS OF CS-4

CSU Sta. No.	USGS Sta. No.	1st Comp.	2nd Comp.
1425625	9.0975	-.1341	.0453
1377280	9.1155	-.1167	.2714
1377230	9.1180	-.0799	.1717
1377200	9.1190	-.3879	.8378
1373900	9.1275	-.0658	.0819
1373055	9.1325	-.8906	-.4286
1373020	9.1345	-.0859	-.0353
1371815	9.1430	-.0537	.0138
1370300	9.1520	-.0616	.0331

TABLE 28 - COEFFICIENTS FOR THE PRINCIPAL COMPONENTS OF CS-6

CSU Sta. No.	USGS Sta. No.	1st Comp.	2nd Comp.
1425625	9.0975	-.1278	-.0209
1377280	9.1155	-.1201	-.2711
1377230	9.1180	-.0831	-.1661
1377200	9.1190	-.3994	-.8374
1373900	9.1275	-.0625	-.0688
1373055	9.1325	-.8857	.4363
1373020	9.1345	-.0853	.0376
1371815	9.1430	-.0567	-.0003
1370300	9.1520	-.0621	-.0283

TABLE 29 - CUMULATIVE PERCENTAGE OF TOTAL VARIATION ACCOUNTED FOR BY THE PRINCIPAL COMPONENTS

Type	Principal component	Cumulative percentage of total variation accounted for
N-4 series	ξ_1	85
	ξ_1 and ξ_2	97
	ξ_1, ξ_2 and ξ_3	98
	ξ_1, ξ_2, ξ_3 and ξ_4	99
N-6 series	ξ_1	85
	ξ_1 and ξ_2	97
	ξ_1, ξ_2 and ξ_3	98
	ξ_1, ξ_2, ξ_3 and ξ_4	99
CN-4 series	η_1	82
	η_1 and η_2	94
	η_1, η_2 and η_3	98
	η_1, η_2, η_3 and η_4	99
CN-6 series	η_1	83
	η_1 and η_2	95
	η_1, η_2 and η_3	98
	η_1, η_2, η_3 and η_4	99
S-4 series	ξ_1	97
	ξ_1 and ξ_2	98
	ξ_1, ξ_2 and ξ_3	99
S-6 series	ξ_1	97
	ξ_1 and ξ_2	98
	ξ_1, ξ_2 and ξ_3	99
CS-4 series	η_1	95
	η_1 and η_2	99
CS-6 series	η_1	95
	η_1 and η_2	99

The means and standard deviations of the series of the principal components for N-4, N-6, CN-4, CN-6, S-4, S-6, CS-4 and CS-6 are given in Table 30.

It is simply proven [12] that if all the means in the target areas during the seeded period have been increased by a certain fraction of the old means, say h , that is, the increase of Q_1 is hQ_1 , of Q_2 is hQ_2, and so on, then the increase in the means of the principal components will also be h . If h is assigned a value of 0.10, then

$$E\{\xi_i^*\} = 1.1\ E\{\xi_i\} \quad ,$$

where $E\{\}$ denotes the expected value of $\{\}$, which is the cloud seeding effect assumed in this study.

TABLE 30 - MEANS AND STANDARD DEVIATIONS OF THE PRINCIPAL COMPONENTS

Type	Principal component	Mean (cfs)	Std. Dev. (cfs)
N-4 series	ξ_1	1316.896	385.728
	ξ_2	23.431	144.526
	ξ_3	-103.167	50.427
	ξ_4	-55.122	37.622
N-6 series	ξ_1	919.996	289.498
	ξ_2	-7.066	106.279
	ξ_3	-103.770	39.834
	ξ_4	-19.400	27.483
CN-4 series	η_1	3566.570	1171.757
	η_2	-616.325	446.487
	η_3	-124.669	238.558
	η_4	41.293	146.087
CN-6 series	η_1	2656.142	853.439
	η_2	-442.328	326.332
	η_3	-118.678	169.248
	η_4	49.830	101.846
S-4 series	ξ_1	-2092.706	865.153
	ξ_2	-95.873	108.688
	ξ_3	30.022	81.462
S-6 series	ξ_1	-1538.060	601.913
	ξ_2	-71.786	74.436
	ξ_3	28.886	55.548
CS-4 series	η_1	-1190.877	459.172
	η_2	-146.711	86.254
CS-6 series	η_1	-849.227	315.594
	η_2	85.939	61.805

For the control region, it is obvious that following the assumption that the means of the runoff stations in the control region remain unchanged,

$$E\{\eta_i^*\} = E\{\eta_i\}$$

where η_i^* is the i^{th} principal component of the control region during the seeded period.

After the principal components in each separate region have been obtained, they are gathered into four major target-control groups as N-4 and CN-4, N-6 and CN-6, S-4 and CS-4, and S-6 and CS-6. For brevity, after the principal components in the target are combined with those in the control, the following symbols will be used:

N-CN-4 - the combination of N-4 and CN-4

N-CN-6 - the combination of N-6 and CN-6

S-CS-4 - the combination of S-4 and CS-4

S-CS-6 - the combination of S-6 and CS-6.

Since it is the principal components that will be utilized in the final test, the computations of the covariance matrices are carried out for these principal components. These are as shown in Tables 31, 32, 33, and 34; also shown are the correlations matrices in Tables 35, 36, 37, and 38.

TABLE 31 - COVARIANCE MATRIX OF N-CN-4 PRINCIPAL COMPONENT SERIES

		N-4				CN-4			
		ξ_1	ξ_2	ξ_3	ξ_4	η_1	η_2	η_3	η_4
N-4	ξ_1	148786.103	-5.194	-1.641	-4.525	361585.644	-32549.149	-7106.856	-8545.409
	ξ_2	-5.194	20887.828	-.361	-.075	31294.727	1427.066	-4668.399	-2250.743
	ξ_3	-1.641	-.361	2542.946	.155	-18240.198	5629.908	2877.776	-679.743
	ξ_4	-4.525	-.075	.155	1415.475	4402.075	-4938.812	-1612.864	149.454
CN-4	η_1	361585.644	31294.727	-18240.198	4402.075	1373015.745	-71.56	57.238	-49.204
	η_2	-32549.149	1427.066	5629.908	-4938.812	-71.561	199350.870	.050	-3.719
	η_3	-7106.856	-4668.399	2877.776	-1612.864	57.238	.050	56910.290	2.404
	η_4	-8545.409	-2250.743	-679.743	149.454	-49.204	-3.719	2.404	21341.511

TABLE 32 - COVARIANCE MATRIX OF N-CN-6 PRINCIPAL COMPONENT SERIES

		N-6				CN-6			
		ξ_1	ξ_2	ξ_3	ξ_4	η_1	η_2	η_3	η_4
N-6	ξ_1	83809.330	3.376	15.820	1.313	191098.859	-20577.629	-10540.852	-2678.418
	ξ_2	3.376	11295.421	2.644	.066	13712.454	3162.736	-2003.334	-963.144
	ξ_3	15.820	2.644	1586.754	.068	-12182.229	1678.320	24.742	-126.575
	ξ_4	1.313	.066	.068	755.354	3884.894	-2718.278	-993.925	121.930
CN-6	η_1	191098.859	13712.454	-12182.229	3884.894	728358.925	20.301	20.187	-14.259
	η_2	-20577.629	3162.736	1678.320	-2718.278	20.301	106493.191	-5.314	-.917
	η_3	-10540.852	-2003.334	24.742	-993.925	20.187	-5.314	28645.205	-.067
	η_4	-2678.418	-963.144	-126.575	121.930	-14.259	-.917	-.067	10372.757

TABLE 33 - COVARIANCE MATRIX OF S-CS-4 PRINCIPAL COMPONENT SERIES

		S-4			CS-4	
		ξ_1	ξ_2	ξ_3	η_1	η_2
S-4	ξ_1	748491.385	-45.282	41.666	338072.405	-12524.935
	ξ_2	-45.282	11813.224	-.485	-11808.907	-1953.006
	ξ_3	-41.666	-.485	6636.209	-636.724	-167.057
CS-4	η_1	338072.405	-11808.907	-636.724	210839.108	7.238
	η_2	-12524.935	-1953.006	-167.057	7.238	7439.863

TABLE 34 - COVARIANCE MATRIX OF S-CS-6 PRINCIPAL COMPONENT SERIES

		S-6			CS-6	
		ξ_1	ξ_2	ξ_3	η_1	η_2
S-6	ξ_1	362299.490	9.116	18.085	162180.856	5816.690
	ξ_2	9.116	5540.858	-.073	-5460.831	1113.406
	ξ_3	18.085	-.073	3985.627	10.105	11.309
CS-6	η_1	162180.856	-5460.831	10.105	99600.481	-.854
	η_2	5816.690	1113.406	11.309	-.854	3819.884

TABLE 35 - CORRELATION MATRIX OF N-CN-4 PRINCIPAL COMPONENT SERIES

		N-4				CN-4			
		ξ_1	ξ_2	ξ_3	ξ_4	η_1	η_2	η_3	η_4
N-4	ξ_1	1.000	-.000	-.000	-.000	.800	-.189	-.077	-.152
	ξ_2	-.000	1.000	-.000	-.000	.185	.022	-.135	-.107
	ξ_3	-.000	-.000	1.000	.000	-.309	.250	.239	-.092
	ξ_4	-.000	-.000	.000	1.000	.100	-.294	-.180	.027
CN-4	η_1	.800	.185	-.309	.100	1.000	-.000	.000	-.000
	η_2	-.189	.022	.250	-.294	-.000	1.000	.000	-.000
	η_3	-.077	-.135	.239	-.180	.000	.000	1.000	.000
	η_4	-.152	-.107	-.092	.027	-.000	-.000	.000	1.000

TABLE 36 - CORRELATION MATRIX OF N-CN-6 PRINCIPAL COMPONENT SERIES

		N-6				CN-6			
		ξ_1	ξ_2	ξ_3	ξ_4	η_1	η_2	η_3	η_4
N-6	ξ_1	1.000	.000	.001	.000	.773	-.218	-.215	-.091
	ξ_2	.000	1.000	.001	.000	.151	.091	-.111	-.089
	ξ_3	.001	.001	1.000	.000	-.358	.129	.004	-.031
	ξ_4	.000	.000	.000	1.000	.166	-.303	-.214	.044
CN-6	η_1	.773	.151	-.358	.166	1.000	.000	.000	-.000
	η_2	-.218	.091	.129	-.303	.000	1.000	-.000	-.000
	η_3	-.215	-.111	.004	-.214	.000	-.000	1.000	-.000
	η_4	-.091	-.089	-.031	.044	-.000	-.000	-.000	1.000

TABLE 37 - CORRELATION MATRIX OF S-CS-4 PRINCIPAL COMPONENT SERIES

		S-4			CS-4	
		ξ_1	ξ_2	ξ_3	η_1	η_2
S-4	ξ_1	1.000	-.000	-.001	.851	-.168
	ξ_2	-.000	1.00	-.000	-.237	-.208
	ξ_3	-.001	-.000	1.000	-.017	-.024
CS-4	η_1	.851	-.237	-.017	1.000	.000
	η_2	-.168	-.208	-.024	.000	1.000

TABLE 38 - CORRELATION MATRIX OF S-CS-6 PRINCIPAL COMPONENT SERIES

		ξ_1	ξ_2	ξ_3	η_1	η_2
		S-6			CS-6	
S-6	ξ_1	1.000	.000	.001	.854	.156
	ξ_2	.000	1.000	-.000	-.232	.242
	ξ_3	.001	-.000	1.000	.001	.003
CS-6	η_1	.854	-.232	.001	1.000	-.000
	η_2	.156	.242	.003	-.000	1.000

5.2 The minimum number of years needed to detect a 10% increase in runoff based on the principal components. The minimum number of years, N^* , for detecting the increase of one-tenth of the old runoff means can be computed from equation (1) again,

$$N^* = \frac{\tau^2}{\underline{\mu}'\underline{V}^{-1}\underline{\mu}} \tag{24}$$

where τ^2 = the noncentrality parameter,

$\underline{\mu} = \underline{\mu}^* - \underline{\mu}_o$,

$\underline{\mu}^*$ = the mean vector of the runoff variables for the seeded period,

$\underline{\mu}_o$ = the mean vector of the runoff variables for the period before seeding, and

$\underline{V}^{-1}$ = the inverse of covariance matrix $\underline{V}$.

The values of τ^2 are given in Table 1.

With this table the number of years needed to detect the increase can be computed easily. The values of N^* are shown in Table 39.

5.3 The application of canonical analysis. In this analysis the set of the runoff variables in the target region is first combined with the set of those in the control region. As for the principal component analysis, the computation of the canonical variables were performed on the CDC 6400 digital computer of the University Computer Center at Colorado State University. The steps in finding the coefficients for the canonical variables were described in Chapter III Section 3.

After the coefficients of the canonical variables for N-4, N-6, CN-4, CN-6, S-4, S-6, CS-4 and CS-6 are all computed and tabulated in Tables 40-47, the canonical series of each region are easily calculated [12].

TABLE 39 - MINIMUM NUMBER OF YEARS TO DETECT THE INCREASE OF 10 PERCENT IN RUNOFF MEAN USING PRINCIPAL COMPONENTS

Type	No. of principal components in target	No. of principal components in control	Value of $\underline{\mu}'\underline{V}^{-1}\underline{\mu}$	τ^2	Minimum number of years to detect the increase, N*	Remarks
N-CN-4	4	4	1.066	11.655	11	The minimum value of N* is obtained from the larger of $N^* = \tau^2/\underline{\mu}'\underline{V}^{-1}\underline{\mu}$ or $N^* = k + 1$ where k is the total number of components in both target and control regions
N-CN-6	4	4	0.813	11.655	15	
S-CS-4	3	2	0.243	8.640	36	
S-CS-6	3	2	0.273	8.640	32	

TABLE 40 - COEFFICIENTS FOR THE CANONICAL VARIABLES OF N-4

CSU Sta. No.	USGS Sta. No.	1st Variable	2nd Variable	3rd Variable	4th Variable
1970000	9.0105	-.003956	-.006628	-.003592	.018543
1960000	9.0110	.003128	-.009783	.011935	-.042535
1866000	9.0165	.005767	-.004685	.026278	.009310
1830000	9.0190	.000796	.003972	-.002342	.002199
1820000	9.0195	-.001320	-.002450	-.001804	.001937
1802730	9.0265	.008752	.008348	.024461	-.012694
1776000	9.0360	.008385	.002618	-.023413	.019209

TABLE 41 - COEFFICIENTS FOR THE CANONICAL VARIABLES OF N-6

CSU Sta. No.	USGS Sta. No.	1st Variable	2nd Variable	3rd Variable	4th Variable
1970000	9.0105	-.006033	-.009805	-.005114	.032451
1960000	9.0110	.004802	-.007516	.011799	-.033462
1866000	9.0165	.009597	.005297	.041092	-.001293
1830000	9.0190	.001003	.003991	-.004721	.002069
1820000	9.0195	-.001910	-.003885	-.001016	.002457
1802730	9.0265	.013825	.025201	.014417	.035857
1776000	9.0360	.010705	-.008078	-.021553	-.008330

TABLE 42 - COEFFICIENTS FOR THE CANONICAL VARIABLES OF CN-4

CSU Sta. No.	USGS Sta. No.	1st Variable	2nd Variable	3rd Variable	4th Variable
1742100	9.0535	.001564	.001900	.003294	.003207
1740000	9.0575	.000620	-.000087	-.002110	-.002931
1720000	9.0595	.000086	-.001640	-.004363	.002621
1666300	9.0645	-.001139	.015690	.001530	.004480
1594260	9.0780	.001374	.001985	-.002575	.003694
1594236	9.0785	-.003596	-.040136	.019047	.013573
1590000	9.0850	.000525	.000354	-.001849	-.001949
1379000	9.1090	.002959	.029446	-.003503	.007790
1378400	9.1100	-.004647	-.030526	.005096	-.010398
1378100	9.1125	.001847	.006202	.009424	.002551
1377825	9.1135	.001334	.011723	.005682	-.002092
1377500	9.1145	-.000174	.000685	-.001047	.000878
1377280	9.1155	-.003380	-.010015	-.008777	-.003425
1377230	9.1180	.008358	.033933	.021453	.033986

TABLE 43 - COEFFICIENTS FOR THE CANONICAL VARIABLES OF CN-6

CSU Sta. No.	USGS Sta. No.	1st Variable	2nd Variable	3rd Variable	4th Variable
1742100	9.0535	.002365	-.001262	.006282	.000515
1740000	9.0575	.000555	-.000926	-.004814	.000489
1720000	9.0595	.000399	-.003421	-.005800	-.000807
1666300	9.0645	-.002081	.019407	-.009901	.012097
1594260	9.0780	.002055	.004230	-.001362	.003426
1594236	9.0785	-.003831	-.049581	.040428	.029201
1590000	9.0850	.000478	-.000866	-.002470	-.002815
1379000	9.1090	.006095	.041344	-.006513	-.013108
1378400	9.1100	-.008394	-.045125	.001749	-.003420
1378100	9.1125	.004031	.013690	.010848	.005814
1377825	9.1135	.001566	.017428	-.000181	-.005258
1377500	9.1145	-.000219	.000494	-.001734	.001375
1377280	9.1155	-.005293	-.011148	-.003944	.002038
1377230	9.1180	.013811	.053074	.011299	.031200

TABLE 44 - COEFFICIENTS FOR THE CANONICAL VARIABLES OF S-4

CSU Sta. No.	USGS Sta. No.	1st Variable	2nd Variable	3rd Variable	4th Variable
1278800	9.1650	-.000949	.010797	-.004734	.000415
1278050	9.1665	.002273	-.002086	.003651	-.002148
1272445	9.1725	.000895	.002056	.008422	-.004012
1077090	9.3440	.000256	.009180	.003705	-.009945
1073480	9.3575	.007460	.009551	-.023825	-.047496
1073436	9.3615	-.003435	-.003435	-.002076	.008598

TABLE 45 - COEFFICIENTS FOR THE CANONICAL VARIABLES OF S-6

CSU Sta. No.	USGS Sta. No.	1st Variable	2nd Variable	3rd Variable	4th Variable
1278800	9.1650	-.001790	.017228	.001080	-.003766
1278050	9.1665	.003301	-.004374	.004401	-.006282
1272445	9.1725	.001264	-.000937	.010721	-.014541
1077090	9.3440	.000707	.007274	-.011061	.011509
1073480	9.3575	.014087	.018233	-.052315	-.056559
1073436	9.3615	-.001675	-.002813	.000808	.013618

TABLE 46.- COEFFICIENTS FOR THE CANONICAL VARIABLES OF CS-4

CSU Sta. No.	USGS Sta. No.	1st Variable	2nd Variable	3rd Variable	4th Variable
1425625	9.0975	.001734	-.004611	.004333	-.005155
1377280	9.1155	-.003347	.055553	.035314	-.034470
1377230	9.1180	-.005054	.005968	.000726	.005480
1377200	9.1190	.003365	-.014545	-.017608	.013770
1373900	9.1275	.000054	-.003457	.002488	-.02948
1373055	9.1325	.000225	.000372	-.000186	-.000378
1373020	9.1345	.002328	.007410	-.007410	-.022485
1371815	9.1430	.004076	.010501	.000507	.023824
1370300	9.1520	.010696	.012852	.036629	.024040

TABLE 47 - COEFFICIENTS FOR THE CANONICAL VARIABLES OF CS-6

CSU Sta. No.	USGS Sta. No.	1st Variable	2nd Variable	3rd Variable	4th Variable
1425625	9.0975	.003565	-.010123	.004390	-.000819
1377280	9.1155	-.007498	.056512	.054781	-.081378
1377230	9.1180	-.006890	.014796	-.000303	.016373
1377200	9.1190	.005324	-.012051	-.020296	.025777
1373900	9.1275	.004037	-.053190	-.028107	-.030019
1373055	9.1325	.000329	.001040	.000236	-.003660
1373020	9.1345	.004450	-.000957	-.031094	.005098
1371815	9.1430	.005299	.012212	.024251	.036120
1370300	9.1520	.010325	.000287	.053491	.006772

The series of the canonical variables are tabulated in Tables 48-55 for N-4, N-6, CN-4, CN-6, S-4, S-6, CS-4, and CS-6, respectively. The means and standard deviations of the canonical series are shown in Table 56.

TABLE 48 - N-4 CANONICAL SERIES (cfs)

Year	ζ_1	ζ_2	ζ_3	ζ_4
1938	5.356	-2.195	-1.045	.827
1939	2.963	-2.067	-1.608	1.737
1940	2.621	-1.618	.602	1.452
1941	4.203	-1.884	3.477	2.474
1942	4.103	- .582	- .923	5.512
1943	3.128	-2.357	- .364	1.256
1944	2.971	-2.235	.303	1.703
1945	3.402	-1.408	- .306	2.703
1946	3.167	-1.729	.509	4.003
1947	5.015	- .291	-1.002	2.790
1948	3.835	.538	- .802	1.186
1949	3.636	-3.039	.383	3.314
1950	3.739	.635	- .523	2.882
1951	4.328	-2.584	.609	2.509
1952	4.910	-2.824	.700	2.171
1953	2.966	-2.111	.030	3.728
1954	1.655	- .943	.533	2.180
1955	2.723	- .476	.674	2.865
1956	3.098	-1.871	- .248	2.906
1957	4.865	-2.033	.654	3.208
1958	3.365	-2.401	.150	3.345
1959	2.979	-1.403	.070	2.835
1960	2.855	-3.081	-1.656	3.486
1961	2.184	-2.026	- .791	2.903
1962	3.978	-3.188	-1.473	1.454
1963	1.504	-1.735	.921	2.158
1964	2.148	-2.119	- .679	3.336
1965	3.473	-3.180	- .720	3.962
1966	1.651	-1.613	- .401	1.842
1967	2.634	-2.746	- .196	2.709

TABLE 49 - N-6 CANONICAL SERIES (cfs)

Year	ζ_1	ζ_2	ζ_3	ζ_4
1938	5.220	-2.656	.059	- .505
1939	2.893	-2.476	- .902	1.870
1940	2.679	-1.385	1.301	.978
1941	4.411	- .711	4.330	.885
1942	4.138	- .805	- .152	3.364
1943	3.198	-2.354	.342	1.723
1944	3.012	-1.995	1.019	1.780
1945	3.747	-1.514	.188	2.513
1946	3.236	-1.534	1.364	2.704
1947	5.197	- .650	- .825	1.721
1948	3.884	.209	- .482	- .298
1949	3.712	-2.711	1.024	3.491
1950	3.721	.334	- .572	1.811
1951	4.513	-2.259	1.273	2.446
1952	5.098	-2.365	1.539	1.697
1953	3.143	-1.963	.609	3.348
1954	1.736	- .761	.828	1.569
1955	2.933	- .278	.877	1.845
1956	3.152	-1.874	.550	1.478
1957	5.089	-1.963	1.283	1.943
1958	3.370	-2.207	.873	2.707
1959	3.080	-1.422	1.006	.546
1960	2.774	-3.571	- .238	1.683
1961	2.289	-2.217	.168	1.377
1962	4.004	-3.549	- .196	.046
1963	1.706	-1.470	1.505	1.636
1964	2.227	-2.279	.342	1.726
1965	3.805	-3.339	1.237	1.362
1966	1.851	-1.664	.974	.259
1967	2.803	-2.707	1.528	.894

TABLE 50 - CN-4 CANONICAL SERIES (cfs)

Year	ε_1	ε_2	ε_3	ε_4
1938	5.491	.115	-1.004	- .420
1939	2.734	- .116	-1.548	1.356
1940	2.615	.354	.971	1.517
1941	4.068	.150	3.984	1.335
1942	4.074	2.026	- .968	4.727
1943	3.220	.655	.902	- .005
1944	3.106	- .109	.309	1.172
1945	3.502	1.417	.684	1.071
1946	3.261	.466	- .008	.919
1947	5.064	2.293	- .718	1.325
1948	4.185	2.310	- .353	.906
1949	3.901	- .062	.090	1.921
1950	3.628	2.314	.803	.889
1951	4.410	.050	.907	1.639
1952	4.792	.306	.297	1.187
1953	3.284	-1.026	.337	2.767
1954	1.706	1.475	.351	.867
1955	2.617	1.851	.501	2.010
1956	3.454	.852	.812	1.785
1957	5.042	- .562	.234	1.013
1958	3.567	-0.	1.252	1.950
1959	3.244	1.619	- .080	1.708
1960	2.788	-1.017	- .883	1.251
1961	2.161	.360	- .346	.701
1962	3.934	- .921	-1.099	.704
1963	1.605	.767	.207	1.260
1964	2.151	.491	.053	1.798
1965	3.539	- .812	.163	3.907
1966	1.896	.599	- .422	.600
1967	2.791	- .149	.551	1.160

TABLE 51 - CN-6 CANONICAL SERIES (cfs)

Year	ε_1	ε_2	ε_3	ε_4
1938	5.435	- .743	- .753	-1.522
1939	2.761	- .672	-1.612	2.013
1940	2.720	.376	.907	1.868
1941	4.347	1.186	3.955	.553
1942	4.185	1.426	-1.182	3.186
1943	3.364	.413	.095	1.183
1944	3.191	- .404	.263	1.457
1945	3.889	.973	- .041	1.240
1946	3.395	- .020	- .033	.823
1947	5.229	1.489	-1.339	.433
1948	4.290	1.883	- .778	- .139
1949	4.025	- .170	- .034	1.808
1950	3.739	2.145	- .209	.809
1951	4.659	.076	.437	2.087
1952	5.008	.190	- .012	1.158
1953	3.472	-1.173	.497	2.826
1954	1.825	1.054	.052	- .140
1955	2.919	1.474	- .004	1.060
1956	3.554	.719	.244	1.561
1957	5.326	- .878	.242	1.018
1958	3.617	.154	.726	2.551
1959	3.364	1.098	- .704	1.214
1960	2.811	-1.515	- .516	.645
1961	2.313	- .274	- .274	.450
1962	3.998	-1.686	- .719	.351
1963	1.888	.542	- .128	1.010
1964	2.322	.302	.169	.812
1965	3.921	-1.187	1.097	1.002
1966	2.035	.174	- .273	- .195
1967	3.040	- .127	1.315	- .522

TABLE 52 - S-4 CANONICAL SERIES (cfs)

Year	ζ_1	ζ_2	ζ_3	ζ_4
1938	4.095	.364	-2.671	-4.194
1939	2.327	.148	- .980	-5.317
1940	2.453	- .015	-1.387	-4.918
1941	4.406	2.663	.354	-2.341
1942	4.391	- .427	-1.419	-4.347
1943	2.809	2.182	-2.294	-3.036
1944	3.989	- .096	-1.276	-1.624
1945	2.834	3.730	-2.042	-3.576
1946	2.414	- .203	-1.678	-4.181
1947	3.075	.861	-3.444	-4.148
1948	3.735	.191	-2.762	-3.410
1949	3.437	.397	-4.331	-1.361
1950	2.313	- .805	- .805	-2.759
1951	1.656	1.645	-2.952	-4.037
1952	4.550	1.260	-3.162	-3.385
1953	1.937	1.592	-1.501	-3.254
1954	1.450	.972	-2.460	-2.073
1955	1.786	1.169	-1.523	-2.373
1956	2.116	1.677	-2.476	-4.210
1957	4.638	2.586	-2.328	-5.720
1958	3.719	1.944	- .092	-2.539
1959	1.478	1.392	-2.539	-4.031
1960	2.794	1.582	-2.113	-3.544
1961	2.280	1.493	-1.499	-3.458
1962	2.926	1.492	-2.984	-3.647
1963	1.642	1.144	-2.166	-3.056
1964	1.992	1.696	-1.201	-3.911
1965	3.494	1.786	-3.343	-2.664
1966	2.378	1.268	-2.392	-3.432
1967	1.625	1.464	-1.932	-3.333

TABLE 53 - S-6 CANONICAL SERIES (cfs)

Year	ζ_1	ζ_2	ζ_3	ζ_4
1938	4.315	.650	-3.827	-1.785
1939	2.608	- .295	-3.195	-3.121
1940	2.712	- .147	-3.104	-3.009
1941	4.493	1.887	- .200	-1.089
1942	4.659	- .473	-3.052	-1.967
1943	3.037	2.460	-2.033	-2.540
1944	4.106	.041	-1.266	-1.033
1945	2.979	3.682	-1.863	-2.466
1946	2.701	- .155	-2.611	-3.445
1947	3.413	1.457	-3.637	-3.310
1948	3.950	.576	-3.158	-2.331
1949	3.596	1.477	-3.813	.509
1950	2.501	- .872	-1.819	-1.651
1951	1.887	2.023	-3.754	-2.471
1952	4.765	1.748	-3.567	-1.583
1953	2.149	1.476	-2.031	-2.269
1954	1.611	1.328	-2.774	- .413
1955	1.982	1.232	-1.707	-1.486
1956	2.338	1.780	-3.107	-2.676
1957	5.055	2.684	-3.450	-4.024
1958	3.792	1.383	.019	-2.808
1959	1.737	1.697	-3.562	-2.468
1960	2.923	1.542	-2.718	-1.512
1961	2.436	1.360	-2.011	-2.307
1962	3.145	1.739	-3.473	-1.878
1963	1.881	1.324	-2.507	-1.724
1964	2.215	1.561	-1.735	-3.363
1965	3.766	2.294	-3.333	- .807
1966	2.578	1.285	-3.051	- .899
1967	1.901	1.538	-2.819	-1.276

TABLE 54 - CS-4 CANONICAL SERIES (cfs)

Year	ε_1	ε_2	ε_3	ε_4
1938	2.930	1.215	1.510	-3.400
1939	1.591	2.091	1.492	-1.727
1940	1.759	.584	3.668	-2.275
1941	3.394	3.652	3.261	- .218
1942	3.803	.792	1.554	-1.400
1943	1.592	2.963	.687	-1.611
1944	3.313	1.341	2.705	-1.182
1945	2.203	4.083	2.156	- .240
1946	1.248	1.090	1.964	-1.471
1947	2.324	2.780	.819	- .605
1948	2.743	.375	.301	- .867
1949	2.928	1.488	- .815	.334
1950	1.582	1.640	.697	-1.436
1951	1.172	3.505	1.263	-1.684
1952	3.543	3.331	.329	- .868
1953	1.218	3.747	1.844	-1.956
1954	.790	1.778	1.233	- .007
1955	1.242	2.389	1.687	- .296
1956	1.121	2.417	.685	-1.332
1957	4.062	3.149	- .353	-3.382
1958	3.096	2.103	2.758	- .973
1959	.921	1.808	1.273	-3.346
1960	1.737	3.652	1.126	-2.610
1961	.962	2.936	1.963	-1.602
1962	2.434	2.865	1.149	-2.768
1963	.634	1.824	.478	-1.287
1964	1.480	2.019	1.262	-2.769
1965	2.462	2.433	.434	-1.807
1966	1.234	1.464	.990	- .835
1967	.924	1.732	.216	-1.053

TABLE 55 - CS-6 CANONICAL SERIES (cfs)

Year	ε_1	ε_2	ε_3	ε_4
1938	3.125	.666	- .268	-1.690
1939	1.867	1.119	.241	- .796
1940	1.871	- .579	1.762	-2.090
1941	3.368	2.396	2.874	.131
1942	3.969	.358	.766	- .335
1943	1.786	2.652	.400	-1.213
1944	3.375	.546	2.335	-1.515
1945	2.292	3.207	2.501	- .102
1946	1.463	.475	1.185	-1.301
1947	2.513	2.392	.927	.182
1948	2.948	.382	.056	- .645
1949	3.056	1.832	- .294	.970
1950	1.764	1.431	.319	- .692
1951	1.245	3.109	1.424	-2.270
1952	3.640	3.039	.844	- .329
1953	1.387	3.068	1.520	-2.353
1954	.848	1.630	1.126	.792
1955	1.357	2.024	1.420	.655
1956	1.223	2.196	.605	-1.273
1957	4.357	3.251	-1.240	-2.029
1958	3.165	1.284	2.821	-1.556
1959	1.145	1.309	- .355	-1.342
1960	1.855	2.945	.362	- .880
1961	1.025	2.263	1.682	-1.794
1962	2.618	2.358	.671	-2.190
1963	.816	1.432	- .026	- .750
1964	1.645	1.454	.473	-2.581
1965	2.718	2.316	- .082	-1.514
1966	1.418	1.063	.549	- .018
1967	1.119	1.632	- .258	.303

TABLE 56 - MEANS AND STANDARD DEVIATIONS OF CANONICAL VARIABLES

Type	Canonical Variable	Mean (cfs)	Std. Dev. (cfs)
N-4 series	ζ_1	3.315	1.000
	ζ_2	-1.819	1.000
	ζ_3	-0.104	1.000
	ζ_4	2.648	1.000
N-6 series	ζ_1	3.421	1.000
	ζ_2	-1.804	1.000
	ζ_3	.695	1.000
	ζ_4	1.620	1.000
CN-4 series	ε_1	3.394	1.000
	ε_2	0.523	1.000
	ε_3	0.199	1.000
	ε_4	1.434	1.000
CN-6 series	ε_1	3.555	1.000
	ε_2	.227	1.000
	ε_3	.046	1.000
	ε_4	1.020	1.000
S-4 series	ζ_1	2.825	1.000
	ζ_2	1.172	1.000
	ζ_3	-2.047	1.000
	ζ_4	-3.463	1.000
S-6 series	ζ_1	3.041	1.000
	ζ_2	1.276	1.000
	ζ_3	-2.639	1.000
	ζ_4	-2.040	1.000
CS-4 series	ε_1	2.015	1.000
	ε_2	2.241	1.000
	ε_3	1.278	1.000
	ε_4	-1.489	1.000
CS-6 series	ε_1	2.166	1.000
	ε_2	1.775	1.000
	ε_3	.811	1.000
	ε_4	-0.941	1.000

Similar to the principal component analysis, it is clear now that,

$$E\{\zeta_i^*\} = (1+h)\ E\{\zeta_i\}$$

where 100h is the percent increase of the runoff means in the target region. If $h = 0.10$, then,

$$E\{\zeta_i^*\} = 1.1\ E\{\zeta_i\}$$

and

$$E\{\varepsilon_i^*\} = E\{\varepsilon_i\}$$

where ε_i^* is the i^{th} canonical variable of the control region for the seeded period.

The covariance matrices of N-CN-4, N-CN-6, S-CS-4, and S-CS-6 are shown in Tables 57-60, respectively. In this analysis the correlation matrices are the same as the covariance matrices since all the canonical variables have unit variances.

5.4 The minimum number of years needed to detect a 10% increase in runoff based on the canonical variables. As discussed before in Section 5.2, the minimum number of years needed to detect the increase can be obtained with the use of Table 1, which gives the value of τ^2 . After the canonical analysis has been performed because the high correlation between target and control variables are desirable here, only the highly correlated canonical variables will be retained for further study.

TABLE 57 - COVARIANCE MATRIX OF N-CN-4 CANONICAL SERIES

		N-4				CN-4			
		ζ_1	ζ_2	ζ_3	ζ_4	ε_1	ε_2	ε_3	ε_4
N-4	ζ_1	1.000	0.	0.	0.	.989	0.	0.	0.
	ζ_2	0.	1.000	0.	0.	0.	.890	0.	0.
	ζ_3	0.	0.	1.000	0.	0.	0.	.847	0.
	ζ_4	0.	0.	0.	1.000	0.	0.	0.	.767
CN-4	ε_1	.989	0.	0.	0.	1.000	0.	0.	0.
	ε_2	0.	.890	0.	0.	0.	1.000	0.	0.
	ε_3	0.	0.	.847	0.	0.	0.	1.000	0.
	ε_4	0.	0.	0.	.767	0.	0.	0.	1.000

TABLE 58 - COVARIANCE MATRIX OF N-CN-6 CANONICAL SERIES

		N-6				CN-4			
		ζ_1	ζ_2	ζ_3	ζ_4	ε_1	ε_2	ε_3	ε_4
N-6	ζ_1	1.000	0.	0.	0.	.990	0.	0.	0.
	ζ_2	0.	1.000	0.	0.	0.	.894	0.	0.
	ζ_3	0.	0.	1.000	0.	0.	0.	.869	0.
	ζ_4	0.	0.	0.	1.000	0.	0.	0.	.768
CN-6	ε_1	.990	0.	0.	0.	1.000	0.	0.	0.
	ε_2	0.	.894	0.	0.	0.	1.000	0.	0.
	ε_3	0.	0.	.869	0.	0.	0.	1.000	0.
	ε_4	0.	0.	0.	.768	0.	0.	0.	1.000

TABLE 59 - COVARIANCE MATRIX OF S-CS-4 CANONICAL SERIES

		S-4				CS-4			
		ζ_1	ζ_2	ζ_3	ζ_4	ε_1	ε_2	ε_3	ε_4
S-4	ζ_1	1.000	0.	0.	0.	.968	0.	0.	0.
	ζ_2	0.	1.000	0.	0.	0.	.771	0.	0.
	ζ_3	0.	0.	1.000	0.	0.	0.	.703	0.
	ζ_4	0.	0.	0.	1.000	0.	0.	0.	.617
CS-4	ε_1	.968	0.	0.	0.	1.000	0.	0.	0.
	ε_2	0.	.771	0.	0.	0.	1.000	0.	0.
	ε_3	0.	0.	.703	0.	0.	0.	1.000	0.
	ε_4	0.	0.	0.	.617	0.	0.	0.	1.000

TABLE 60 - COVARIANCE MATRIX OF S-CS-6 CANONICAL SERIES

		S-6				CS-6			
		ζ_1	ζ_2	ζ_3	ζ_4	ε_1	ε_2	ε_3	ε_4
S-6	ζ_1	1.000	0.	0.	0.	.969	0.	0.	0.
	ζ_2	0.	1.000	0.	0.	0.	.777	0.	0.
	ζ_3	0.	0.	1.000	0.	0.	0.	.696	0.
	ζ_4	0.	0.	0.	1.000	0.	0.	0.	.568
CS-6	ε_1	.969	0.	0.	0.	1.000	0.	0.	0.
	ε_2	0.	.777	0.	0.	0.	1.000	0.	0.
	ε_3	0.	0.	.696	0.	0.	0.	1.000	0.
	ε_4	0.	0.	0.	.568	0.	0.	0.	1.000

For example, consider the case of S-CS-4. The correlation between the first canonical variable in S-4 and the first canonical variable in CS-4 is found to be 0.968, which is the maximum of all the correlations between the canonical variables for S-CS-4. If it is decided to use only these two canonical variables in the test, then all one needs to do is the following. From Table 56, obtain

$$\underline{\mu}_o = \begin{bmatrix} 2.825 \\ 2.015 \end{bmatrix} .$$

Assuming that there is an increase of 10% in the means of the target region and the means in the control region remain unchanged, then, the mean vector for the seeding period can be obtained as

$$\underline{\mu}^* = \begin{bmatrix} 3.107 \\ 2.015 \end{bmatrix} .$$

Now $\underline{\mu} = (\underline{\mu}^* - \underline{\mu}_o)$, that is,

$$\underline{\mu} = \begin{bmatrix} 3.107 \\ 2.015 \end{bmatrix} - \begin{bmatrix} 2.825 \\ 2.015 \end{bmatrix}$$

$$\underline{\mu} = \begin{bmatrix} 0.282 \\ 0.0 \end{bmatrix} .$$

Compute the inverse of the covariance matrix of the first canonical variables in the target and control regions, $\underline{V}^{-1}$. In this case,

$$\underline{V}^{-1} = \begin{bmatrix} 15.879 & -15.371 \\ -15.371 & 15.879 \end{bmatrix}$$

and then compute,

$$\underline{\mu}'\underline{V}^{-1}\underline{\mu} = [0.282 \quad 0.0] \begin{bmatrix} 15.879 & -15.371 \\ -15.371 & 15.879 \end{bmatrix} \begin{bmatrix} 0.282 \\ 0.0 \end{bmatrix}$$

$$= 1.271 \quad .$$

TABLE 61 - INVERSE OF COVARIANCE MATRIX OF N-CN-4 CANONICAL SERIES

		N-4				CN-4			
		ζ_1	ζ_2	ζ_3	ζ_4	ϵ_1	ϵ_2	ϵ_3	ϵ_4
N-4	ζ_1	45.706	0.	0.	0.	-45.203	0.	0.	0.
	ζ_2	0.	4.810	0.	0.	0.	-4.281	0.	0.
	ζ_3	0.	0.	3.539	0.	0.	0.	-2.997	0.
	ζ_4	0.	0.	0.	2.429	0.	0.	0.	-1.863
CN-4	ϵ_1	-45.203	0.	0.	0.	45.706	0.	0.	0.
	ϵ_2	0.	-4.281	0.	0.	0.	4.810	0.	0.
	ϵ_3	0.	0.	-2.997	0.	0.	0.	3.539	0.
	ϵ_4	0.	0.	0.	-1.863	0.	0.	0.	2.429

TABLE 62 - INVERSE OF COVARIANCE MATRIX OF N-CN-6 CANONICAL SERIES

		N-6				CN-6			
		ζ_1	ζ_2	ζ_3	ζ_4	ϵ_1	ϵ_2	ϵ_3	ϵ_4
N-6	ζ_1	50.251	0.	0.	0.	-49.749	0.	0.	0.
	ζ_2	0.	4.981	0.	0.	0.	-4.453	0.	0.
	ζ_3	0.	0.	4.084	0.	0.	0.	-3.549	0.
	ζ_4	0.	0.	0.	2.438	0.	0.	0.	-1.872
CN-6	ϵ_1	-49.749	0.	0.	0.	50.251	0.	0.	0.
	ϵ_2	0.	-4.453	0.	0.	0.	4.981	0.	0.
	ϵ_3	0.	0.	-3.549	0.	0.	0.	4.084	0.
	ϵ_4	0.	0.	0.	-1.872	0.	0.	0.	2.438

TABLE 63 - INVERSE OF COVARIANCE MATRIX OF S-CS-4 CANONICAL SERIES

		S-4				CS-4			
		ζ_1	ζ_2	ζ_3	ζ_4	ϵ_1	ϵ_2	ϵ_3	ϵ_4
S-4	ζ_1	15.879	0.	0.	0.	-15.371	0.	0.	0.
	ζ_2	0.	2.466	0.	0.	0.	-1.901	0.	0.
	ζ_3	0.	0.	1.977	0.	0.	0.	-1.390	0.
	ζ_4	0.	0.	0.	1.615	0.	0.	0.	-.996
CS-4	ϵ_1	-15.371	0.	0.	0.	15.879	0.	0.	0.
	ϵ_2	0.	-1.901	0.	0.	0.	2.466	0.	0.
	ϵ_3	0.	0.	-1.390	0.	0.	0.	1.977	0.
	ϵ_4	0.	0.	0.	-.996	0.	0.	0.	1.615

TABLE 64 - INVERSE OF COVARIANCE MATRIX OF S-CS-6 CANONICAL SERIES

		S-6				CS-6			
		ζ_1	ζ_2	ζ_3	ζ_4	ϵ_1	ϵ_2	ϵ_3	ϵ_4
S-6	ζ_1	16.383	0.	0.	0.	-15.875	0.	0.	0.
	ζ_2	0.	2.524	0.	0.	0.	-1.961	0.	0.
	ζ_3	0.	0.	1.940	0.	0.	0.	-1.350	0.
	ζ_4	0.	0.	0.	1.476	0.	0.	0.	-.839
CS-6	ϵ_1	-15.875	0.	0.	0.	16.383	0.	0.	0.
	ϵ_2	0.	-1.961	0.	0.	0.	2.524	0.	0.
	ϵ_3	0.	0.	-1.350	0.	0.	0.	1.940	0.
	ϵ_4	0.	0.	0.	-.839	0.	0.	0.	1.476

The degrees of freedom here are 2 and 28, which are the number of canonical variables and the number of observations less the number of canonical variables, respectively. With these degrees of freedom, the value of τ^2 is found to be 5.468, at the level of significance $\alpha = 0.05$ and power $\beta = 0.50$. Now from

$$N^* = \frac{\tau^2}{\underline{\mu}'\underline{V}^{-1}\underline{\mu}}$$

the value of N^* is obtained as

$$N^* = \frac{5.468}{1.271} = 4.3 = 5 \text{ years} ,$$

since N^* must be an integer. These values of N^* are shown in Table 65.

The previous results are based on the assumption that the sample mean is the same as the population mean during the non-seeded period. Now consider what effect a violation of this assumption would have on the results.

Suppose the true population mean is not equal to the sample mean. Instead it lies at the upper extremity of the 50% confidence interval established for the sample mean of the non-seeded period. Then a 10% increase in the true population mean results in a larger absolute increase than does a 10% increase in the assumed population mean (simply because the actual population mean is larger than the assumed population mean).

In the northern region, an actual 10% increase in the true population mean yields a 14.2% increase in the assumed population mean. This results in a reduction in the number of observations required to detect a change. The number of observations would be reduced to 50% of the previously determined number of observations. Similarly, in the southern region an

TABLE 65 - MINIMUM NUMBER OF YEARS TO DETECT THE INCREASE OF 10 PERCENT IN RUNOFF MEANS USING CANONICAL VARIABLES

Type	No. of canonical variables in target	No. of canonical variables in control	Value of $\underline{\mu}'\underline{V}^{-1}\underline{\mu}$	τ^2	Minimum number of years to detect the increase, N*	Remarks
N-CN-4	1	1	5.037	5.468	3	The minimum value of N* is obtained from the larger of $N^* = \tau^2/\underline{\mu}'\underline{V}^{-1}\underline{\mu}$ or $N^* = k + 1$ where k is the total number of variables in both target and control
	2	2	5.197	7.640	5	
	3	3	5.198	9.646	7	
	4	4	5.368	11.655	9	
N-CN-6	1	1	5.877	5.468	3	
	2	2	6.040	7.640	5	
	3	3	6.060	9.646	7	
	4	4	6.124	11.655	9	
S-CS-4	1	1	1.271	5.468	5	
	2	2	1.305	7.640	6	
	3	3	1.388	9.646	7	
	4	4	1.581	11.655	9	
S-CS-6	1	1	1.423	5.468	4	
	2	2	1.465	7.640	6	
	3	3	1.690	9.646	7	
	4	4	1.752	11.655	9	

actual 10% increase in the true population mean yields a 15.6% increase in the assumed population mean, and a corresponding reduction in the required number of observations by 60 percent.

Now, suppose that the true population mean lies at the lower end of the 50% confidence interval. Then a 10% increase in the true population mean results in a smaller absolute increase than does a 10% increase in the assumed population mean.

In the northern region, an actual 10% increase in the true population mean yields a 5.8% increase in the assumed population mean. This results in an increase in the number of observations required to detect a change. The number of observations would be increased by a factor of three. Similarly, in the southern region an actual 10% increase in the true population mean yields a 4.4% increase in the assumed population mean, and the number of observations required would be increased by a factor of 5.2.

In view of the above discussion, it is seen that if the number of observations is calculated by assuming different values for the population mean a distribution is obtained. The median number of observations will be the same as that number obtained by using the sample mean of the non-seeded period.

Chapter VI

CONCLUSIONS

It was the objective of this study to develop a technique for detection of a geographically widespread change in a minimum amount of time.

It was found that a combination of techniques, namely canonical analysis and multivariate T^2 test was the most effective means to provide positive results in the least time. Assuming a 10% increase in runoff, 3 and 4 years are the minimum number of years needed for significance in the Upper Basin of the Colorado and the San Juan Mountains, respectively.

A word of caution is needed at this point. If the effect of precipitation management is to produce exactly a uniform 10% increase in runoff the use of only one set of canonical components is very efficient. However, if the increase is not uniform, it is safer to use several canonical components. With more canonical components, however, the number of years needed for significance increases.

It is apparent that there exists a trade-off between power of the test and representativity of the tested variables. This is well illustrated by the combined use of principal components analysis and the T^2 test. The first three or four principal components account for 99% of the total variation in the target regions. These sets of components so to speak, are 99% representative. The number of years calculated from the T^2 test is much higher than the corresponding figure for the same number of canonical components. This number of years could be decreased by using only one principal component, which already accounts on the average for 90% of the total variation. (This number was not actually calculated but the validity of the statement can be inferred from examination of the covariance matrices).

Note that when the χ^2-test is applied to each target station with the best correlated control station, the lowest minimum number of years is found to be seven in both northern and southern regions. Again, a single station is, of course, poorly representative of the entire region. The technique (canonical components - T^2 test) improves both the power of the test and the regional representativity of the tested variable, over what it would have been even with the best single target control pair.

The results from the use of four-months or six-months spring runoff are very similar. Nevertheless, better results are obtained with the six-months runoff series, particularly in the southern area.

LIST OF SYMBOLS

Symbol	Meaning
Q_i	Runoff at station i (i is the number in the 'Seq. No.' column in Table 2)
q_i	Observation of Q_i
$\bar{q}_i$	The mean of Q_i
$q_{i,m}$	The m^{th} observation of Q_i
$\underline{Q}$	Column vector of runoff at all stations
$\underline{q}_i$	Column vector of the i^{th} observation of $\underline{Q}$
$\bar{\underline{q}}$	Mean vector of observations of $\underline{Q}$
N	Number of observations of non-seeded period
N*	Minimum number of years for detecting a 10% increase in the runoff means of seeded period
N-4	Four-month runoff series in the northern target region (the 4 months are: April, May, June, and July)
N-6	Six-month runoff series in the northern target region (the 6 months are: March, April, May, June, July and August)
CN-4	Four-month runoff series in the northern control region
CN-6	Six-month runoff series in the northern control region
S-4	Four-month runoff series in the southern target region
S-6	Six-month runoff series in the southern target region
CS-4	Four-month runoff series in the southern control region
CS-6	Six-month runoff series in the southern control region
N-CN-4	The combination of N-4 and CN-4
N-CN-6	The combination of N-6 and CN-6
S-CS-4	The combination of S-4 and CS-4
S-CS-6	The combination of S-6 and CS-6
k	Total number of runoff variables, i.e., the number of all target and control variables
h	The fractional increase in the runoff mean
E{}	The expected value of {}
p	The number of runoff variables in target (or control) region in the principal component analysis
p_1	The number of runoff variables in target region
p_2	The number of runoff variables in control region
$\underline{\beta}_i$	Column vector of coefficients for computing the i^{th} principal component

LIST OF SYMBOLS - Continued

Symbol	Meaning
β_{ij}	Coefficient of runoff at station j in the computation of the i^{th} principal component
I	Identity matrix
$\underline{V}$	Covariance matrix of runoff variables
$\underline{V}^{-1}$	Inverse of $\underline{V}$
$\underline{W}$	$\underline{V}^{-1}$
ξ_i	The i^{th} principal component of target region before seeding
ξ_i^*	The i^{th} principal component of target region for seeded period
η_i	The i^{th} principal component of control region before seeding
η_i^*	The i^{th} principal component of control region for seeded period
$\xi_{i,m}$	The m^{th} data point of ξ_i
$\eta_{i,m}$	The m^{th} data point of η_i
λ_i	The amount of variance accounted for by the i^{th} principal component
ζ_i	The i^{th} canonical variable of target region before seeding
ζ_i^*	The i^{th} canonical variable of target region for seeded period
ε_i	The i^{th} canonical variable of control region before seeding
ε_i^*	The i^{th} canonical variable of control region for the seeded period
$\zeta_{i,m}$	The m^{th} data point of ζ_i
$\varepsilon_{i,m}$	The m^{th} data point of ε_i
θ_i	Correlation between ζ_i and ε_i
$\underline{\alpha}_i$	Vector of coefficients for computing ζ_i
$\underline{\gamma}_i$	Vector of coefficients for computing ε_i
$\alpha_{i,j}$	Coefficient of runoff at station j (target region) in the computation of ζ_i
$\gamma_{i,j}$	Coefficient of runoff at station j (control region) in the computation of ε_i
$\underline{\mu}^*$	Runoff mean vector for the seeded period
$\underline{\mu}_o$	Runoff mean vector for the non-seeded period
$\underline{\mu}$	$\underline{\mu}^* - \underline{\mu}_o$
$\underline{\mu}'$	Transpose of $\underline{\mu}$
$\sum_{i=1}^{N}$	Summation from $i=1$ to $i=N$
$\prod_{i=1}^{N}$	Product from $i=1$ to $i=N$
τ^2	Noncentrality parameter
$\hat{}$	Estimated value

LIST OF SYMBOLS - Continued

Symbol	Meaning
'	Transpose of a matrix
σ_{ii}	Variance of runoff variable Q_i
σ_{ij}	Covariance of runoff variables Q_i and Q_j
*	Of seeded period
cfs	Cubic feet per second

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Key Words: Statistical discrimination, regional hydrologic change, seasonal runoff, precipitation management, evaluation

Abstract: The object of this study is to find answers to the following questions: What is the appropriate statistical test for a regional target-control technique of evaluation? What is a suitable method for reduction of an originally large number of variables? Which of the Upper Basin of the Colorado River or the San Juan Mountains is a more suitable area of operations, if the effectiveness of precipitation management is to be detected as quickly as possible? The results of this research study show: 1. The T^2-test is the appropriate test for multiple target-control technique of evaluation. 2. The canonical anlysis is the suitable method for the reduction of a large number of original variables. 3. The Upper Basin of the Colorado River is preferable under the assumption of an equal percentage of increase in runoff. However, if the percentage increase in the southern area is at least 1.2 times as large as in the northern area (and recent publications suggest that this ratio is probably around 3) then the southern area is preferable. Based on the T^2-test, the minimum number of years for detecting an increase of 10 percent in spring runoff means are three years in the Upper Basin of the Colorado River, and four years in the San Juan Mountains.

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