ANALYSIS OF PRECIPITATION DATA IN THE UPPER COLORADO RIVER BASIN

by

Richard A. Schleusener

Engineering Research
Colorado State University

and

Loren W. Crow
Consulting Meteorologist
900 E Louisiana
Denver, Colorado

CIVIL ENGINEERING SECTION
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

October 1961

CER61RAS52

PAST AND PROBABLE FUTURE VARIATIONS IN STREAM FLOW IN THE UPPER COLORADO RIVER

I. Summary and Conclusions

Morris E. Garnsey,
Project Director

II. A Study of the Statistical Predictability of Stream Runoff in the Upper Colorado River Basin

Paul R. Julian,
Research Staff,
High Altitude Observatory,
University of Colorado

III. Some General Aspects of Fluctuations of Annual Runoff in the Upper Colorado River Basin

Vujica M. Yevdjevich,
Engineering Research,
Colorado State University

IV. Probability Analysis Applied to the Development of a Synthetic Hydrology for the Colorado River

Margaret R. Brittan,
Assistant Professor of Statistics,
University of Denver

V. Analysis of Precipitation Data in the Upper Colorado River Basin

Richard A. Schleusener,
Engineering Research,
Colorado State University
and
Loren W. Crow,
Consulting Meteorologist
Denver, Colorado

SPONSORS

This project was sponsored by the State of Colorado, supported by it and by the States of New Mexico, Utah and Wyoming, acting through the Upper Colorado River Commission

ANALYSIS OF PRECIPITATION DATA IN THE UPPER COLORADO RIVER BASIN

by

Richard A. Schleusener
Engineering Research
Colorado State University

and

Loren W. Crow
Consulting Meteorologist
900 E Louisiana
Denver, Colorado

Civil Engineering Section
Colorado State University
Fort Collins, Colorado

October 1961

CER61RAS52

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES-Continued

ABSTRACT

A sample of daily precipitation and temerature data from 30 weather observing locations in or near the Upper Colorado River Basin have been placed on cards and partially analyzed by computer techniques. The sample represents a total of 1660 station years and analytical conclusions give a good representation of the climatic ranges for this area. Frequency of precipitation at multiple time intervals for each location are presented. Major storms having a recurrence less than once per year have been found to contribute significantly to runoff in the Upper Colorado River. Preliminary techniques for adjusting actual precipitation to more closely relate to runoff are presented and further refinements are anticipated. Variations in moisture sources have been studied.

ACKNOWLEDGEMENTS

The authors wish to thank the State of Colorado and the other States of the Upper Colorado River for the financial support which has made this study possible.

Special thanks are due Mr. Joseph Berry, Weather Bureau Climatologist for the State of Colorado, for his assistance in supplying and editing many of the original weather records which were used as a basis of this study.

A special note of thanks is due the many unpaid cooperative weather observers of the U. S. Weather Bureau, who collected the basic data used in this study and without whose cooperation this report would not have been possible.

I. INTRODUCTION

Work at Colorado State University has been concerned with analyses of existing climatological data in order to provide a refinement of basic data useful in hydrologic studies of the Upper Colorado River Basin.

Climatological data from many stations in the Upper Colorado River Basin have been collected for many years by unpaid cooperative observers of the U. S. Weather Bureau. Records of daily maximum and minimum temperatures, precipitation, snowfall, and other data are available for about 50 to 60 years prior to 1960. Since 1948 the Weather Bureau has placed all such data on IBM cards for machine tabulation and analysis. Prior to 1948 however, climatological data were in tabular form only, not in a format suitable for machine computation and analysis.

The general procedure followed in this study has been to place weather records prior to 1948 on IBM cards in a format suitable for machine computation and analysis as a first step study. These data were reduced to storm totals and from the reduced storm totals various frequency analyses were performed. Details of the procedures followed in processing the precipitation data are included in the appendix.

A. WEATHER STATIONS ANALYZED

Precipitation data from 30 stations in an near the Upper Colorado River Basin were analyzed in this study. Table I summarizes the stations and years included in this analysis. As shown in Table I about 608,000 cards were used in the analysis. Of these cards, about 470,000 were prepared at Colorado State University as a part of this study.

The locations of the stations used in this study are shown in Figure 1. Figure 1 also shows the inclusive dates for which data were available for this study.

It should be noted that some parts of this report (such as parts of III and IV) are based on analyses from stations from Colorado only, since they were performed by hand prior to the availability of machine-processed data from all stations.

B. WHEN AND WHERE PRECIPITATION OCCURS

Fall rains, winter snows, and summer showers are the precipitating mechanisms which produce the water which runs back toward the ocean in the Colorado River from the collection basin of the Colorado River Watershed. This general concept of timing is an oversimplification when applied to individual stations, but the stream flow of the Colorado River at Lee Ferry is an integrated measure of the runoff yield of a large area. This watershed area is characterized by having rather extreme variations in elevation, distances from major moisture sources, and the localized effects of surrounding terrain and windward exposure of the locations where precipitation amounts have been measured.

The pattern of monthly precipitation amounts is shown in Figure 2 for three groupings of stations representing three general elevation levels. Rather uniform timing is indicated at all three levels. The months of November and June stand out as low average months, with June being the lowest month in the entire year. September is a relatively low month, which tends to divide the summer shower period from the fall rain period.

TABLE I

SUMMARY OF CARD PUNCHING COMPLETED

Stations In	Number Of Stations	STATION-YEARS Punched By CSU	USWB	Total
Colorado				
Western Slope	18	839	170	1,009
Fort Collins	1	70		70
New Mexico	1	42	12	54
Utah	5	113	137	250
Wyoming	5	219	58	277
	Total Station-Years	1,283	377	1,660
Total Number of Cards (Approximately)		470,000	138,000	608,000

The late winter and spring period of heavier precipitation throughout the year generally occurs from broad general storms covering thousands of square miles of cross-sectional area. The relatively high summer precipitation peaks of July and August are a result of local shower activity, each storm covering only a small area. The summer showers occur during the period when evaporation rates are very high.

Contrasts in the amounts of precipitation can be noted easily in that the high level stations tend to have precipitation amounts between two and three times greater than those at low level stations. The contrast of low evaporation at high elevations and high evaporation at low elevations accentuates the importance of high elevation collection of precipitation.

C. DEPTH OF PRECIPITATION REQUIRED TO PRODUCE THE MEASURED FLOW IN THE UPPER COLORADO RIVER

The measurement of runoff in acre feet allows a quick computation of the total quantity of runoff in inches that takes place over a year's time to produce the total annual runoff at any given point where measurements are made along a river basin. If 12 inches of water over one acre equals one acre foot, then one inch of runoff over 12 acres would also equal an acre foot of water. With 640 acres per square mile, one inch of runoff would produce 53.33 acre feet of water. (640 divided by 12 = 53.33).

At high elevations where precipitation amounts are high and evaporation rates are low, the yield of runoff is high. For instance, the mean annual flow of the Animas River at Durango represents 17.7 inches from the 692 square miles above that gaging station. By contrast, the mean annual flow of the Paria River at Lee Ferry represents a runoff from a 1550 square mile area of only 0.3 inch.

The mean annual flow measured at Lee Ferry, Arizona (the terminal point of the Upper Basin) represents a total annual runoff of ONLY 2.3 inches for the entire 109,889 square mile watershed above that point.

The general range of runoff from low years to high years would be between approximately one inch and three inches. This runoff comes from an area which receives precipitation quantities ranging from only a few inches to over 30 inches.

From this analysis it can be seen that any one single storm covering this broad area which is capable of producing one inch of runoff over the whole watershed above Lee Ferry, would change the flow by approximately 6 million acre feet. Thus it is important to analyze carefully the precipitation records of the past to determine when and how runoff yields are produced from the precipitation patterns that move through this area.

D. GENERAL EVAPORATION AND RUNOFF RELATIONSHIPS

The capacity of air to contain moisture is directly related to temperature. The absolute quantity of moisture which can be carried in vapor form in saturated air at 32^{0} F is less than one-fifth the amount that can be carried in saturated air at 80^{0} F.

The process of precipitating moisture out of the atmosphere takes advantage of this fundamental fact by carrying warm moist air upward and cooling it. The fractional portion of absolute moisture which is in excess of the amount needed to produce 100 per cent saturation at the cooler temperatures falls out. This phenomenon is well illustrated in the lifting and cooling accomplished by strong vertical updrafts in a summer thunderstorm which can "expel" very heavy rain in a localized area for a brief period of time. The precipitation process constitutes an <u>outflow</u> of moisture from the atmosphere.

When any particular air mass is not producing precipitation or being held at or near 100 per cent saturation, it can absorb additional water in vapor form, and there is an <u>inflow</u> of moisture into the atmosphere as it moves past any moisture source.

In the upper basin of the Colorado River the total hours of active precipitation and 100 per cent saturation constitute a very, very small fraction of the 8760 hours in an entire year. During all the other hours when saturation is <u>less than 100 per cent</u>, the air mass can accept and carry away moisture which can enter it by either direct evaporation from moist surfaces or transpiration from plant life.

The altitude range between the lowest elevation in the watershed above Glen Canyon and the mountain peaks at the rim of the Continental Divide is such that there is an extremely wide range in evapotranspiration losses at different points in the watershed and at different times of the year. Table II presents the average monthly temperature at 2000-foot intervals within the air mass covering the upper watershed of the Colorado River throughout the year.

Looking first at the 14,000-foot elevation, which is nearly the same as the highest peaks, we note that average monthly temperatures remain

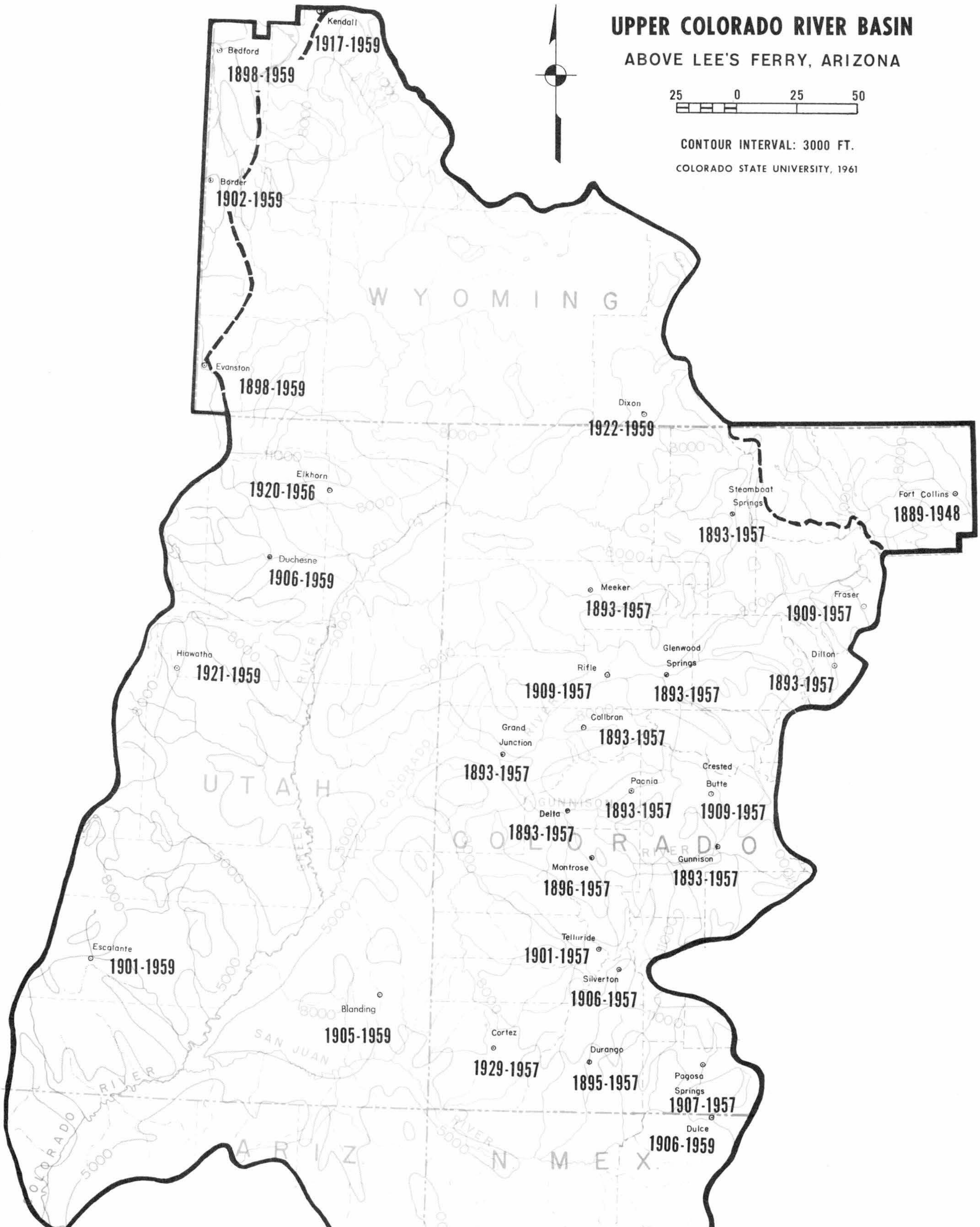


Fig. 1. Stations and inclusive dates for meteorological data used in this study.

STATION GROUPINGS BY ELEVATION

High Level Above 8,000'	Middle Level 6,200' to 7,999'		Low Level Below 6,200'
Silverton	Gunnison	Bedford	Paonia
Dillon	Kendall	Dixon	Border
Crested Butte	Hiawatha	Meeker	Cortez
Telluride	Pagosa Spgs.	Glenwood Spgs. *	Blanding
Fraser	Dulce	Durango	Rifle
Steamboat Spgs. *	Evanston	Collbran	Montrose
	Elkhorn		Escalante
			Duchesne
			Grand Junction
			Delta
			Ft Collins

*Arbitrarily included in next higher elevation group due to abnormally large precipitation amounts.

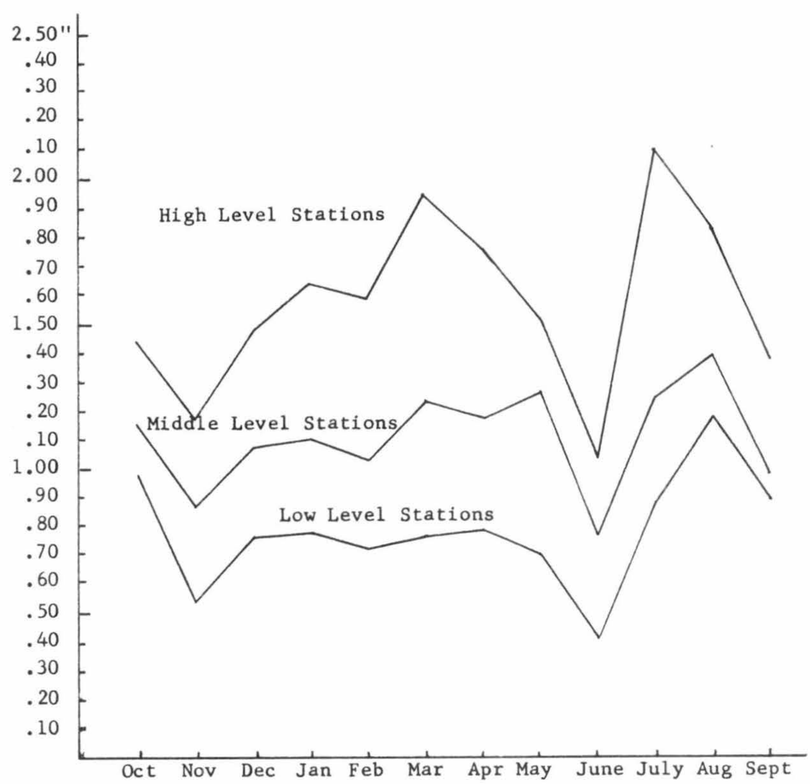
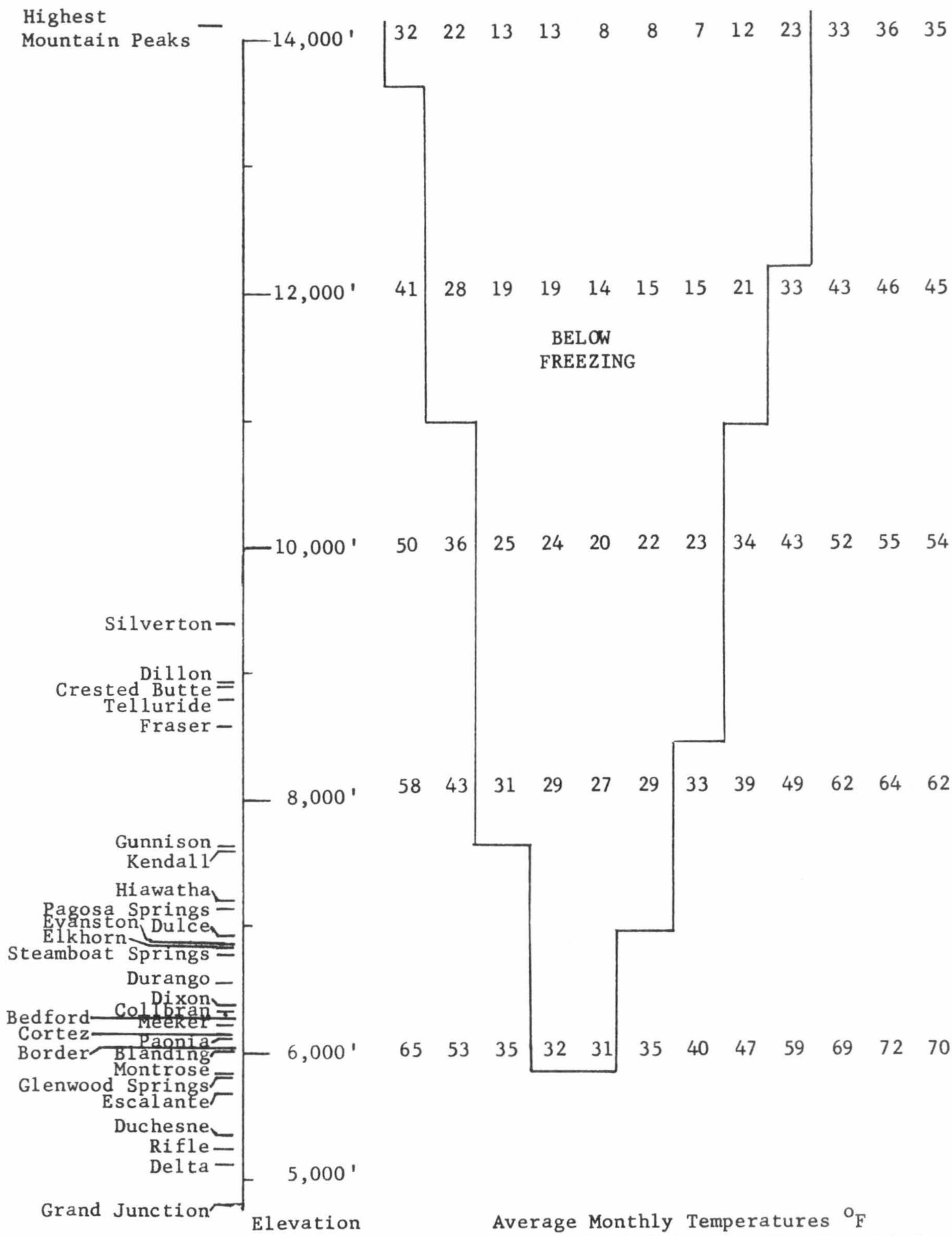


Fig. 2. Group means of median monthly precipitation amounts throughout the year from October through September for three elevation groups.

TABLE II

Average monthly temperatures at 2,000-foot intervals within the air mass which moves against or envelopes the primary collection basin of the Colorado River throughout the year--based on a three-year sample of data obtained by radiosondes released from Grand Junction, Colorado.



Average Monthly Temperatures °F

Elevation	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
14,000'	32	22	13	13	8	8	7	12	23	33	36	35
12,000'	41	28	19	19	14	15	15	21	33	43	46	45
10,000'	50	36	25	24	20	22	23	34	43	52	55	54
8,000'	58	43	31	29	27	29	33	39	49	62	64	62
6,000'	65	53	35	32	31	35	40	47	59	69	72	70
5,000'												

below freezing for nine months out of the year, and the other three months have temperatures only slightly above freezing. The capacity of the transitory air to carry water away from these highest elevations is extremely limited and can be considered as negligible throughout the entire year. It is easy to see from Table II how snowpack can build up at the higher elevations during the cold winter months.

By contrast, at the 6000-foot level all months have temperatures above freezing, with the exception of December and January, and these two months are near the freezing level. The warmer months at the lower elevations have temperatures and dry air capable of accepting tremendous quantitites of moisture either through direct evaporation or transpiration from plant life.

The lower elevations of the watershed above Glen Canyon Reservoir are also characterized by being made up of generally flat sandy soil with tremendous capacity for absorbing large quantities of rainfall and preventing any direct runoff. The many dry washes are perennial evidence to this fundamental fact. Only in the instances of extremely heavy local thunderstorms do these dry washes carry any water, and many times this water disappears long before it reaches the main stem of the Colorado River. Almost all of the water which does enter the soil returns in delayed evaporation into the atmosphere before ever reaching the Colorado River.

Little is known about actual rates of evaporation. However, some rough approximations can be made about the fractional portion of the observed precipitation which is lost to evapotranspiration in this particular watershed.

The entire watershed loses over 80 per cent.
The area below 5000 feet loses over 90 per cent.
The area above 11,000 feet loses less than 20 per cent.

During the winter there is a much greater contrast between low elevations and high elevations. This is first due to the marked contrast in precipitation amounts, the higher elevation stations recording nearly three times as much as the low elevation stations. Immediate evaporation at high elevations is negligible, and the delayed evaporation tends to be consolidated in the amount of moisture entering the soil either at the beginning or end of the snowpack season.

At the elevations above 10,000 feet, all the storms which occur from approximately early November through mid-April tend to accumulate as if they were one large storm, and the runoff from this accumulation also can be treated as if it were one large storm.

II. FREQUENCY ANALYSES

One of the objectives of the study was to determine the frequency distribution of precipitation during various periods of time. The results of these frequency analyses are given in Figures 3 - 32 which are presented in this section. The inclusive dates for which meteorological data were used are presented in Figure 1.

In Figures 3 - 15 and Figures 19 - 30, the frequency analyses are presented by giving the mean, standard deviation, and coefficient of variation. As pointed out later in this report (see especially section II B below) the precipitation data are not normally distributed and usually are positively skewed. In spite of this fact, for convenience the standard deviation is presented with the mean to give an estimate of the probability of occurrence of the event.

For normally distributed data the mean ± one standard deviation should include about two-thirds of the cases; the mean ± two standard deviations should include about 95 per cent of all the cases; and the mean ± three standard deviations should include about 99 per cent of all the cases. To illustrate, from Figure 3 we note that the mean annual precipitation at Gunnison is 10.54 inches, with a standard deviation of 2.21 inches. Thus, approximately two-thirds of all years should fall approximately within the limit of 10.54 ± 2.21 inches, etc.

It should be emphasized that these frequencies are approximate only, since most of the data are positively skewed and do not follow a normal distribution.

The coefficient of variation, defined as the standard deviation divided by the mean, gives a measure of the relative variability of the data.

A. ANNUAL PRECIPITATION

1. Observed Annual Precipitation

Figure 3 shows that marked differences in annual precipitation occur at stations which are relatively close together. For example, Silverton, Colorado (elevation 9400 feet), has the highest annual precipitation with 24.60 inches per year, while Montrose (elevation 5830 feet), geographically nearby, but on the opposite side of a ridge of high terrain, has a much lower value of 9.75 inches per year. The coefficient of variation is higher for stations in the southern part of the Upper Colorado River Basin. The values vary from 0.3 for stations in southern Colorado and Utah to a value of about 0.2 for stations in northern Colorado and Wyoming.

2. Number of Storms Occurring During a Water Year

One storm period consists of a number of consecutive days with precipitation greater than a trace in any 24 hour period.

Figure 4 shows that the variations in the number of storms are similar to the variations in mean annual precipitation. High-altitude stations such as Silverton and Telluride receive more storms during the year than nearby low-altitude stations such as Delta and Grand Junction. A greater number of storms per year occur at stations in the northern part of the basin such as Kendall and Bedford than in southern stations such as Durango and Pagosa Springs.

3. Annual Precipitation Contributing to Runoff

a. Adjusting Actual Precipitation Data To "Precipitation Contributing To Runoff" Data - Basically there is a very direct relationship between precipitation and runoff. Large amounts of precipitation are required to produce large amounts of runoff. However, the range of errors sustained in working with total known precipitation records to derive co-related runoff indicates considerable room for refinement. One very large source of error comes from the assumption that one particular rain gage with a cross sectional catchment area of less than one square foot can represent the true measurement of precipitation for an area of several thousand square miles.

A second cause for error is the wide variation in precipitation timing. One storm which produces four inches of rain on one day can deliver far more runoff than 40 storms on 40 different days each producing .10 inch.

With the advent of computer facilities it is believed possible to reduce the second cause of error by adjusting actual precipitation records to give resultant values which are more directly related to runoff. Small storms which will contribute little or no runoff can be eliminated from the adjusted precipitation record. A large part of the rainfall from large storms returns to the atmosphere by evapotranspiration, and only the balance moves to the streams as runoff.

The quantities to be deducted from individual storm totals to account for evaporation losses

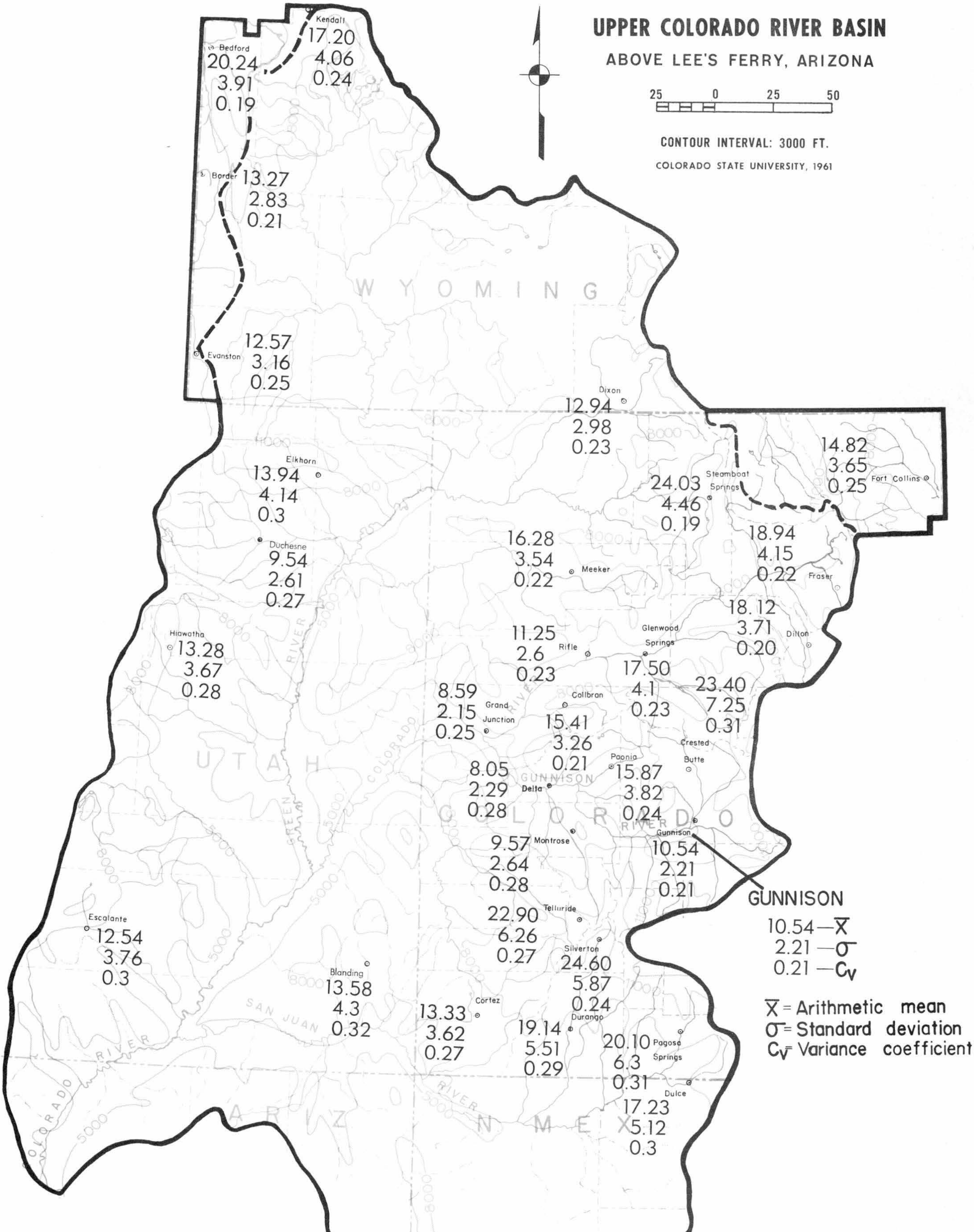


Fig. 3 Mean, standard deviation, and coefficient of variation of annual precipitation (in inches) during a water year.

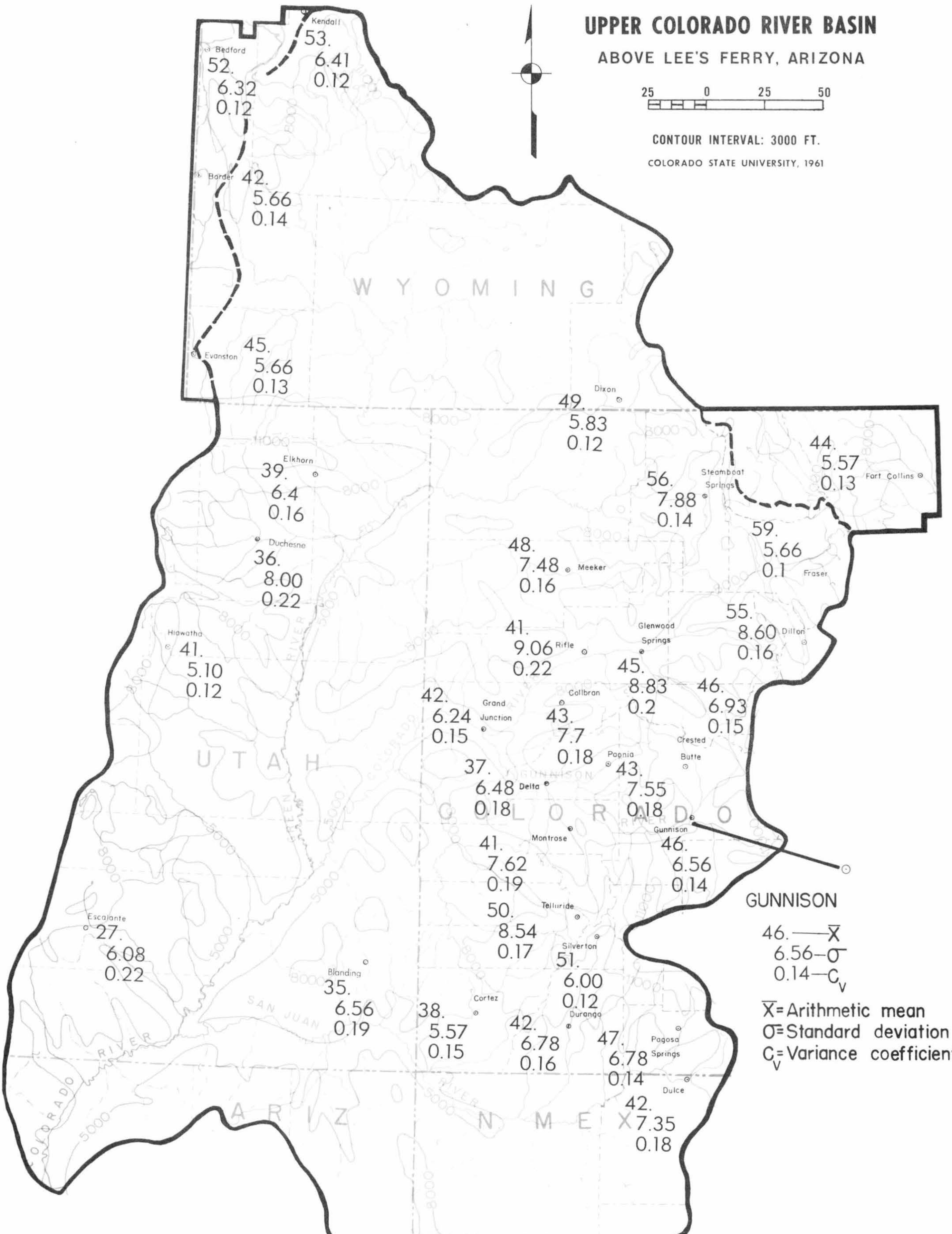


Fig. 4 Mean, standard deviation, and coefficient of variation of the number of storms received during a water year. See accompanying text for definition of a storm period.

should vary for different times of the year and also for different elevations. As a first approximation of the right order of magnitude, the "dropout" values shown in Table III have been used as an initial step to illustrate such an adjustment technique.

On an annual basis precipitation-year totals corresponding to the water-year runoff totals at Glen Canyon Reservoir should ordinarily include data from September through August. Only very heavy storms in early September contribute to the current September runoff measured at Glen Canyon. (See September, 1927).

Prior to the development of this adjustment table, tests were made on samples of data covering rather small watersheds which have little or no diversion above gaging stations.

For instance, the actual September-August precipitation at Fraser for water year 1957 was 28.08 inches. When these data are adjusted, the net result is 23.37 inches. The runoff for a small 32.8 square mile watershed measured on St. Louis Creek near Fraser was equal to 21.58 inches. This was a wet year, and it is believed that some of the moisture was carried over into 1958.

From September to August, 1958, the actual precipitation total was 17.23 inches. The adjusted total was only 12.16, and the runoff was 15.00 inches. This indicates a benefit in runoff from 1957 precipitation. The two years combined show actual precipitation of 45.31 inches. The adjusted two-year precipitation was 35.53 inches, and runoff 36.58 inches.

Similar relationship problems for small watersheds near Dillon and near Silverton also gave good results for typical near average conditions and for wet and dry year extremes. Watersheds at low elevations studied included the Paria River in Utah and Chevelon Creek on the Little Colorado River in Arizona. At these two locations the median annual runoff is less than one-half inch, and practically all the annual precipitation must be deducted in the adjustment.

The "dropout" values as shown in Table III have been used only to illustrate the technique. Further gradation for elevation is recommended. It is also expected that subsequent test and criticisms by experienced hydrologists familiar with precipitation and runoff relationships in the Colorado River Basin will permit refinement.

Subsequent developments in evaporation measurement techniques may give indications of more correct "dropouts" to be applied.

b. Value Of "Precipitation Contributing To Runoff" - The effect of making such reductions in observed precipitation amounts as estimates of the losses by evaporation and transpiration are shown in Figure 5. Figure 5 shows that high-altitude stations contribute significantly more runoff than do nearby low-altitude stations. For example, Figure 5 shows more than 16 inches contributing to runoff from Telluride while the nearby station of Montrose yields about only one inch of precipitation contributing to runoff.

c. Number Of Storms Contributing To Runoff - Figure 6 shows the number of storm periods that are effective in contributing to runoff after the observed precipitation data are reduced for estimated evapotranspiration losses by the values shown in Table III. The Number of storm periods contributing to runoff follows a pattern that is similar to the precipitation contributing to runoff shown in Figure 5. The stations at higher elevations, such as Telluride, have many more periods each year in which storms contribute to runoff than nearby low elevation stations, such as Delta or Montrose.

The coefficient of variation for the low-altitude stations is much higher than for the high-elevation stations.

TABLE III

AMOUNTS TO BE DEDUCTED (INCHES) FROM INDIVIDUAL STORMS TO ADJUST ACTUAL PRECIPITATION TO "PRECIPITATION CONTRIBUTING TO RUNOFF"

	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
High Level Stations	-.5	-.5	no deduction						-.3	-.3	-.5	-.5
			cumulative →									
Middle Level Stations	-.7	-.7	-.5	-.2	-.2	-.2	-.2	-.5	-.5	-.5	-.7	-.7
				cumulative →								
Low Level Stations	-.8	-.8	-.6	-.6	-.4	-.4	-.6	-.6	-.6	-.6	-.8	-.8

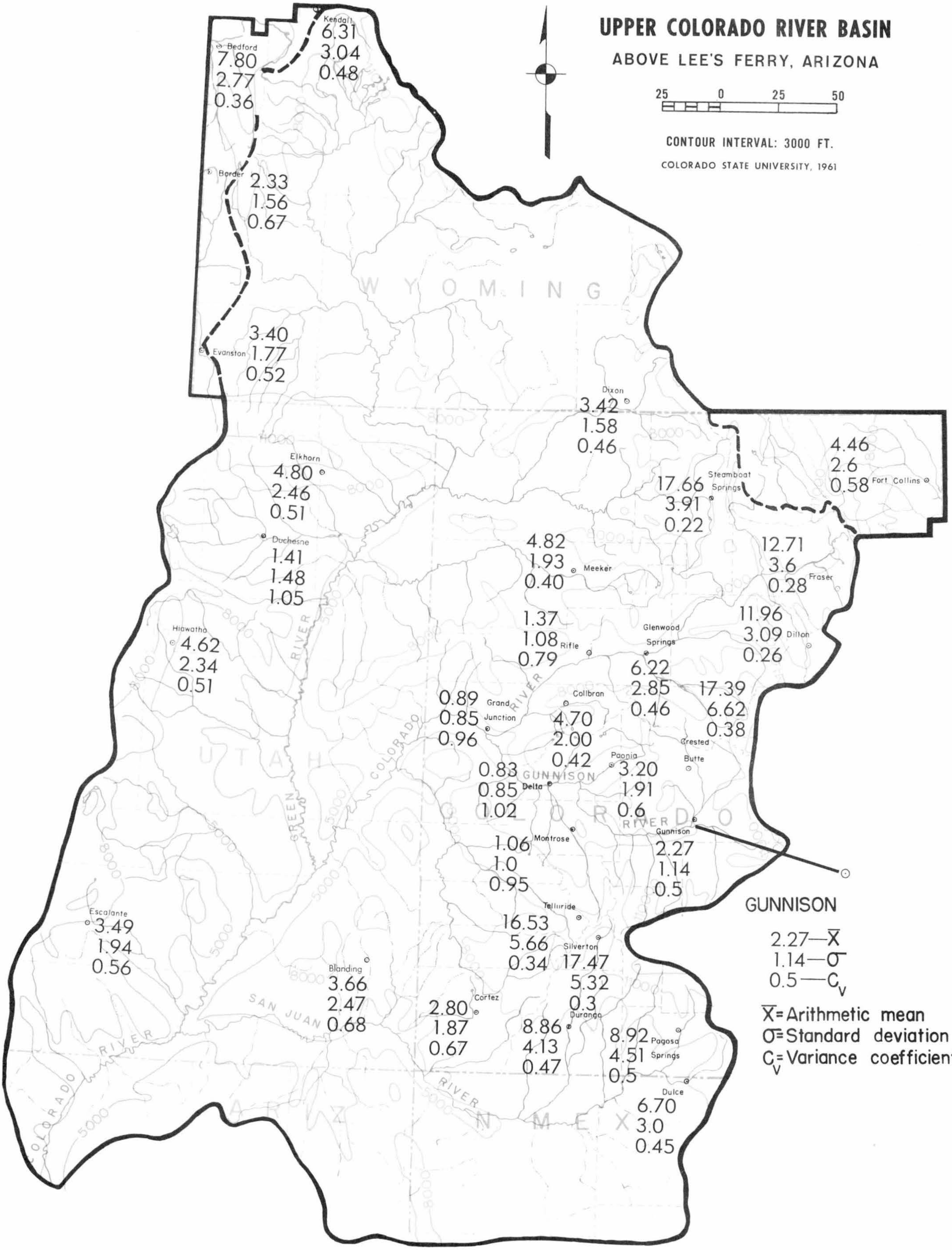


Fig. 5 Mean, standard deviation, and coefficient of variation of "Annual precipitation (in inches) contributing to runoff" during a water year, determined by making certain reductions in observed precipitation for assumed evapotranspiration losses. See accompanying text for details.

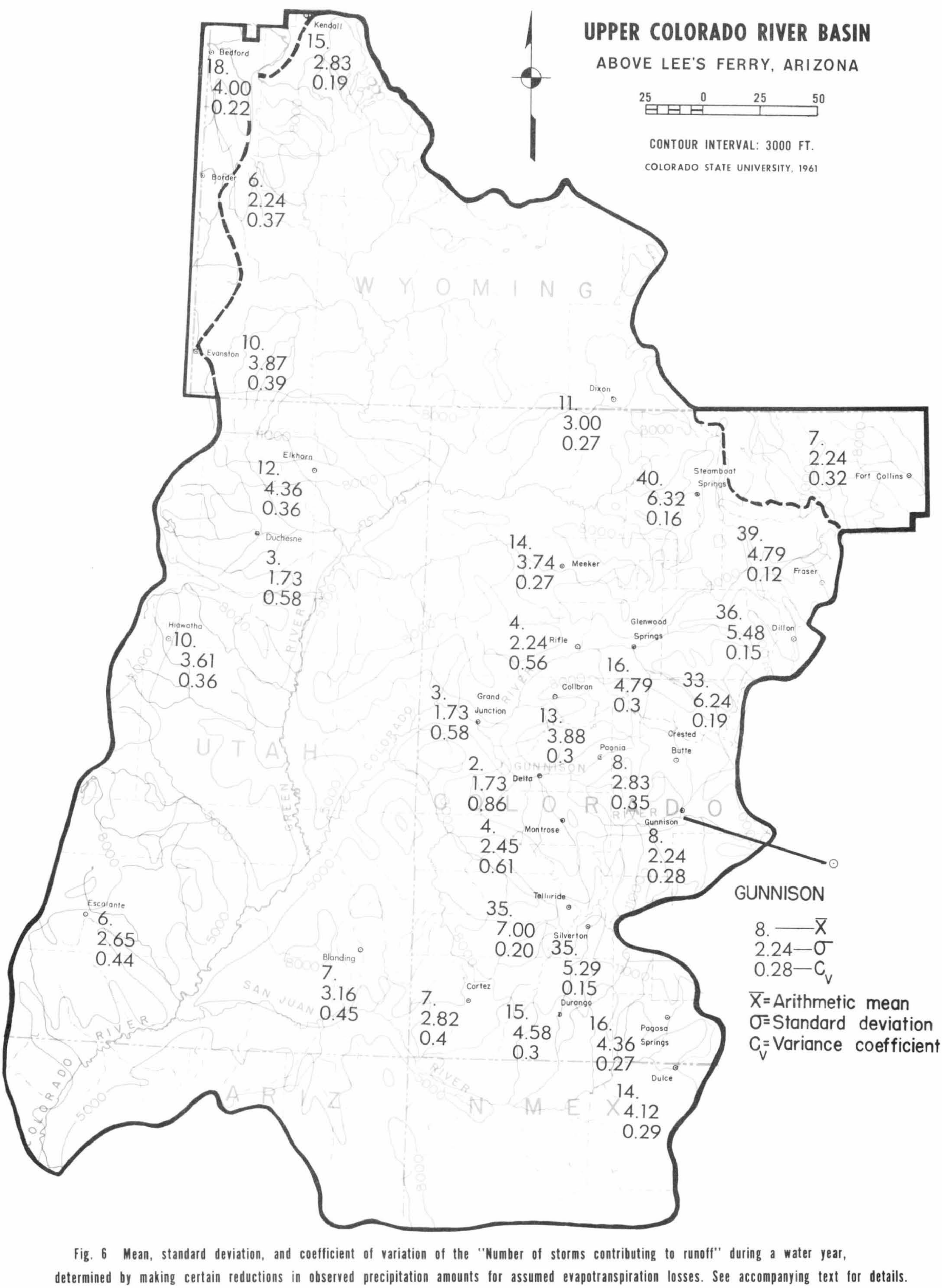


Fig. 6 Mean, standard deviation, and coefficient of variation of the "Number of storms contributing to runoff" during a water year, determined by making certain reductions in observed precipitation amounts for assumed evapotranspiration losses. See accompanying text for details.

B. DIFFERENCE BETWEEN AVERAGE AND MEDIAN PRECIPITATION TOTALS IN SEMI-ARID CLIMATES

It has been the policy in most climatological data publications, including this one, to present precipitation quantities as average precipitation by monthly totals for any particular location. This average (mean) is obtained by the simple mechanics of adding together all of the monthly totals for the series of record available and dividing that total number by the quantity of months used in the sample. This is a very easy method for obtaining a general indication of the precipitation that may be expected in a given area, but it can be definitely misleading if the array of precipitation quantities throughout the record is made up of a few very high monthly totals and the majority of the monthly totals ranging around a much smaller value. The median value of monthly precipitation gives a better indicator of what to expect in the semi-arid region from which the Colorado River obtains its runoff.

The median is defined as the point in a total sample which has half the number of individual values above it and half below it.

In any semi-arid region which has many small storms and few large ones, the median value is consistently below the mean value. This fact is illustrated in Table IV, which shows the difference between monthly mean and monthly median in the three elevation groups used in Figure 2.

The difference between the average and the median at high level stations per month is 0.24 inch. The difference at the middle level stations is 0.20 inch, and at low level stations, 0.18 inch. The most extreme case of relative importance is the month of June at low elevation stations when the arithmetic average is 0.61, while the median is only 0.40. Even at the high elevation stations the difference between average and median is generally greater than 10 per cent of the monthly values.

C. PERCENTAGE OF STORM PERIODS GIVING VARIOUS FRACTIONS OF TOTAL ANNUAL RAINFALL

1. Percentage of Storm Periods Giving 25 Per Cent of the Annual Rainfall for the Water Year

The percentage of the number of storm periods required to give one-fourth of the annual rainfall for the year is shown in Figure 7. Figure 7 shows the skewed nature of the annual precipitation amounts. In every case approximately 65 per cent of the storm periods are required to produce 25 per cent of the annual rainfall. Conversely, 75 per cent of the annual rainfall is contributed by only 35 per cent of all storms.

Fort Collins, a station on the eastern slope of the Continental Divide, requires an exceptionally high percentage, 74.6 per cent of all storms, to produce 25 per cent of its annual precipitation.

2. Percentage of Storm Periods Giving 50 Per Cent of the Annual Rainfall for the Water Year

For all the stations analyzed, approximately 85 per cent of the storm periods are required to produce 50 per cent of the annual rainfall for the water year. The other 50 per cent is produced by only 15 per cent of all storms. (Figure 8).

3. Percentage of Storm Periods Giving 75 Per Cent of the Annual Rainfall for the Water Year

Approximately 95 per cent of the storm periods are required to produce 75 per cent of the

TABLE IV

COMPARISON OF GROUP MEAN OF AVERAGE MONTHLY PRECIPITATION AND GROUP MEAN OF MEDIAN MONTHLY PRECIPITATION FOR THREE ELEVATION GROUPS (See Fig. 2)

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
High Level Stations												
Average	1.69	1.36	1.77	1.94	1.86	2.18	2.04	1.65	1.34	2.25	2.16	1.59
Median	1.45	1.18	1.47	1.64	1.59	1.95	1.76	1.51	1.03	2.10	1.82	1.37
Difference	.24	.18	.30	.30	.27	.23	.28	.14	.31	.15	.34	.22
Middle Level Stations												
Average	1.36	.99	1.29	1.35	1.24	1.37	1.36	1.40	1.03	1.47	1.62	1.18
Median	1.16	.88	1.08	1.10	1.03	1.23	1.19	1.26	.77	1.23	1.39	.96
Difference	.20	.11	.21	.25	.21	.14	.17	.14	.26	.24	.23	.22
Low Level Stations												
Average	1.17	.74	.93	.95	.84	.92	.95	.92	.61	1.03	1.35	1.08
Median	.99	.54	.77	.78	.73	.78	.79	.70	.40	.88	1.17	.89
Difference	.18	.20	.16	.17	.11	.14	.16	.22	.21	.15	.18	.19

annual rainfall for the water year. Therefore, the other 25 per cent of the annual rainfall comes from about 5 per cent of all storms.

The extreme case is again Fort Collins, where 25 per cent of annual rainfall is produced by only ~~20~~ 2.9 per cent of all storms. (Figure 9).

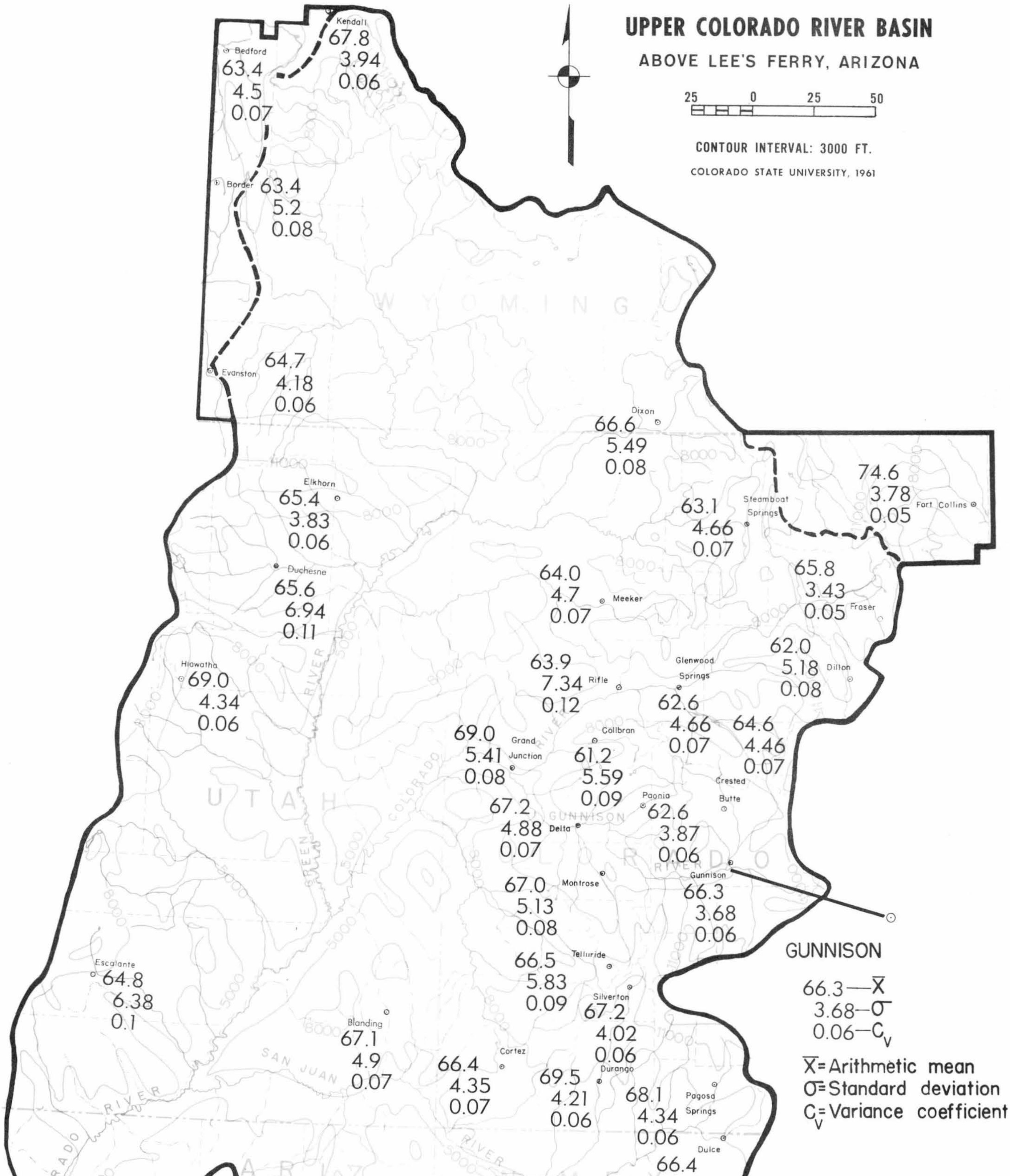


Fig. 7 Average percentage, standard deviation and coefficient of variation of the number of storm periods giving 25 per cent of rainfall for the water year.

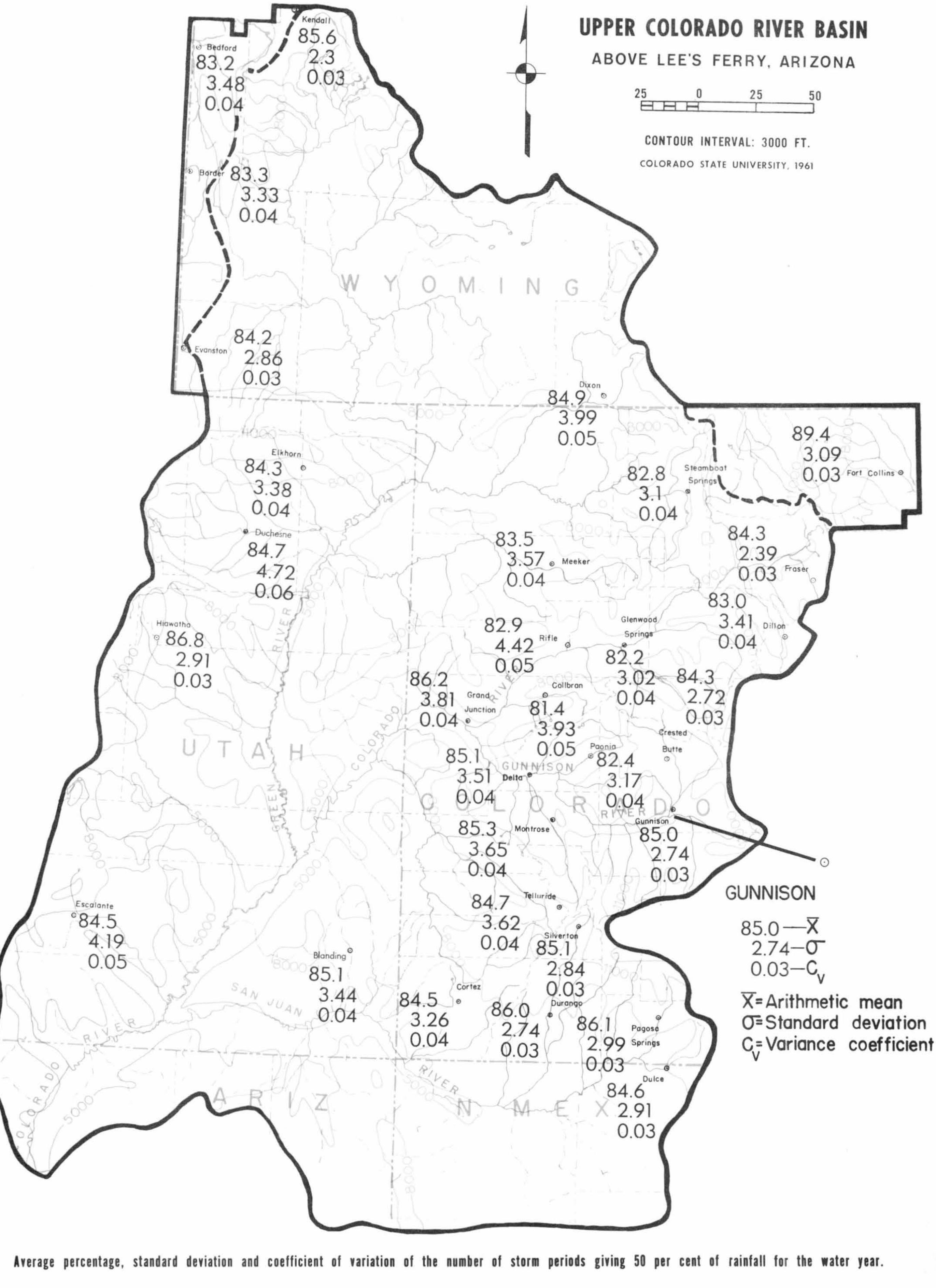


Fig. 8 Average percentage, standard deviation and coefficient of variation of the number of storm periods giving 50 per cent of rainfall for the water year.

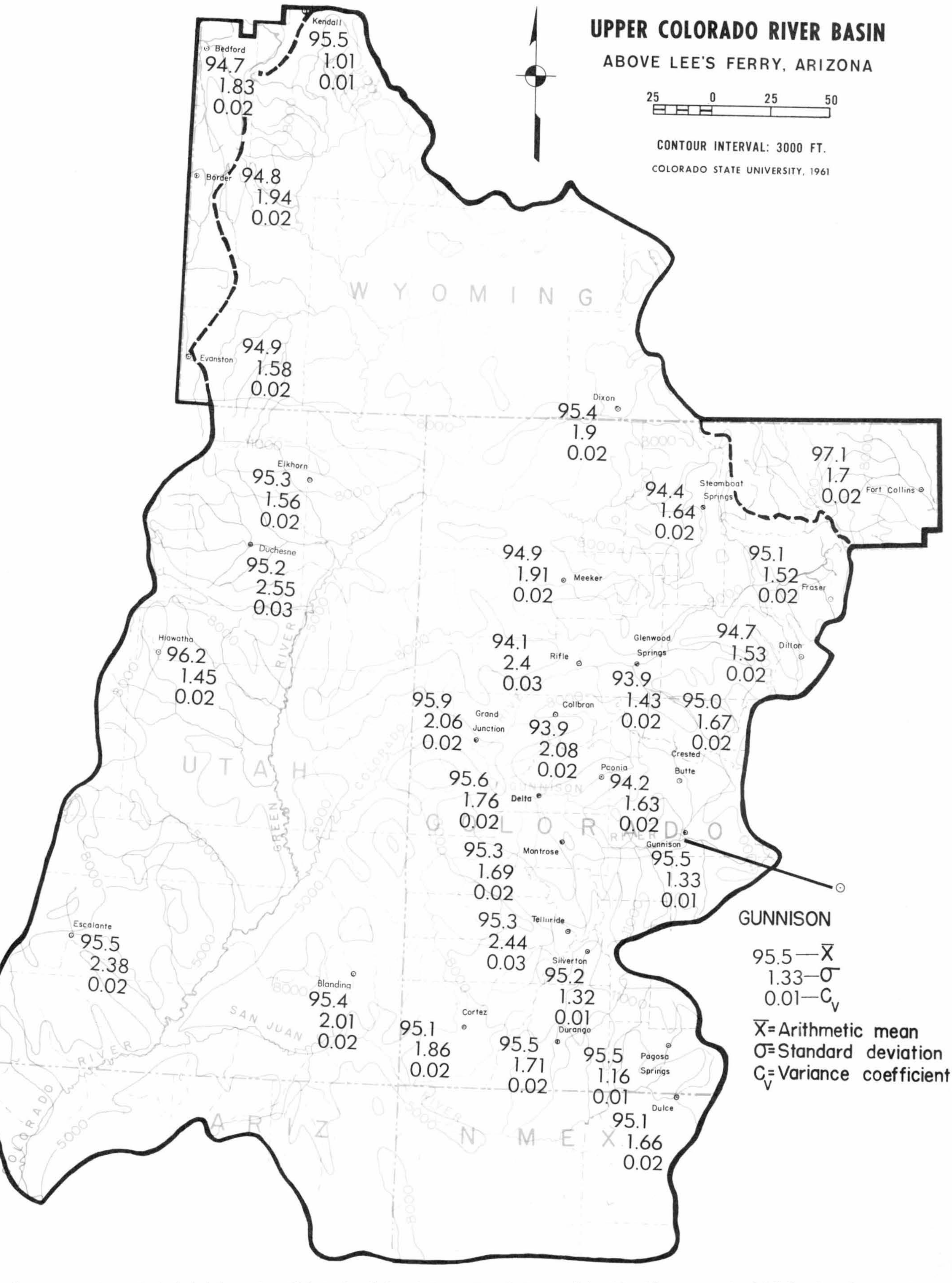


Fig. 9 Average percentage, standard deviation and coefficient of variation of the number of storm periods giving 75 per cent of rainfall for the water year.

D. DATES WITHIN THE WATER YEAR FOR ACQUIRING VARIOUS AMOUNTS OF PRECIPITATION

1. Dates of Acquiring 5 inches of Precipitation During a Water Year

Figure 10 shows the mean number of days after the 1st of October required to accumulate 5 inches of precipitation. The number in parentheses indicates the per cent of total years of record in which 5 inches or more precipitation was received during the water year. Only for the stations Grand Junction, Delta, Duchesne, Escalante, and Montrose were there any years in which less than 5 inches of precipitation was received.

2. Dates of Acquiring 10 inches of Precipitation During a Water Year

The mean date, standard deviation in days, and coefficient of variation of acquiring 10 inches of precipitation during a water year are shown in Figure 11. High-level stations such as Silverton and Telluride received more than 10 inches of precipitation for each water year for the period of record, while stations such as Grand Junction, Delta, and Montrose received 10 inches during the water year less than 50 per cent of the time.

3. Dates of Acquiring 15 inches of Precipitation During a Water Year

Only the high-altitude stations in Colorado and the stations in Wyoming received more than 15 inches of precipitation during the water year more than 50 per cent of the time. Low-altitude stations such as Grand Junction, Delta, and Montrose never received more than 15 inches of precipitation during the period of record. (Figure 12).

4. Dates of Acquiring 20 inches of Precipitation During a Water Year

Most of the stations in the Upper Colorado River Basin did not receive 20 inches of precipitation at least half the time. Only Silverton, Telluride, and Bedford, Crested Butte and Steamboat Springs received more than 20 inches of precipitation half the time. (Figure 13).

5. Dates of Acquiring 25 inches of Precipitation During a Water Year

Figure 14 shows that the occurrence of 25 inches of annual precipitation is very rare throughout the Upper Colorado River Basin.

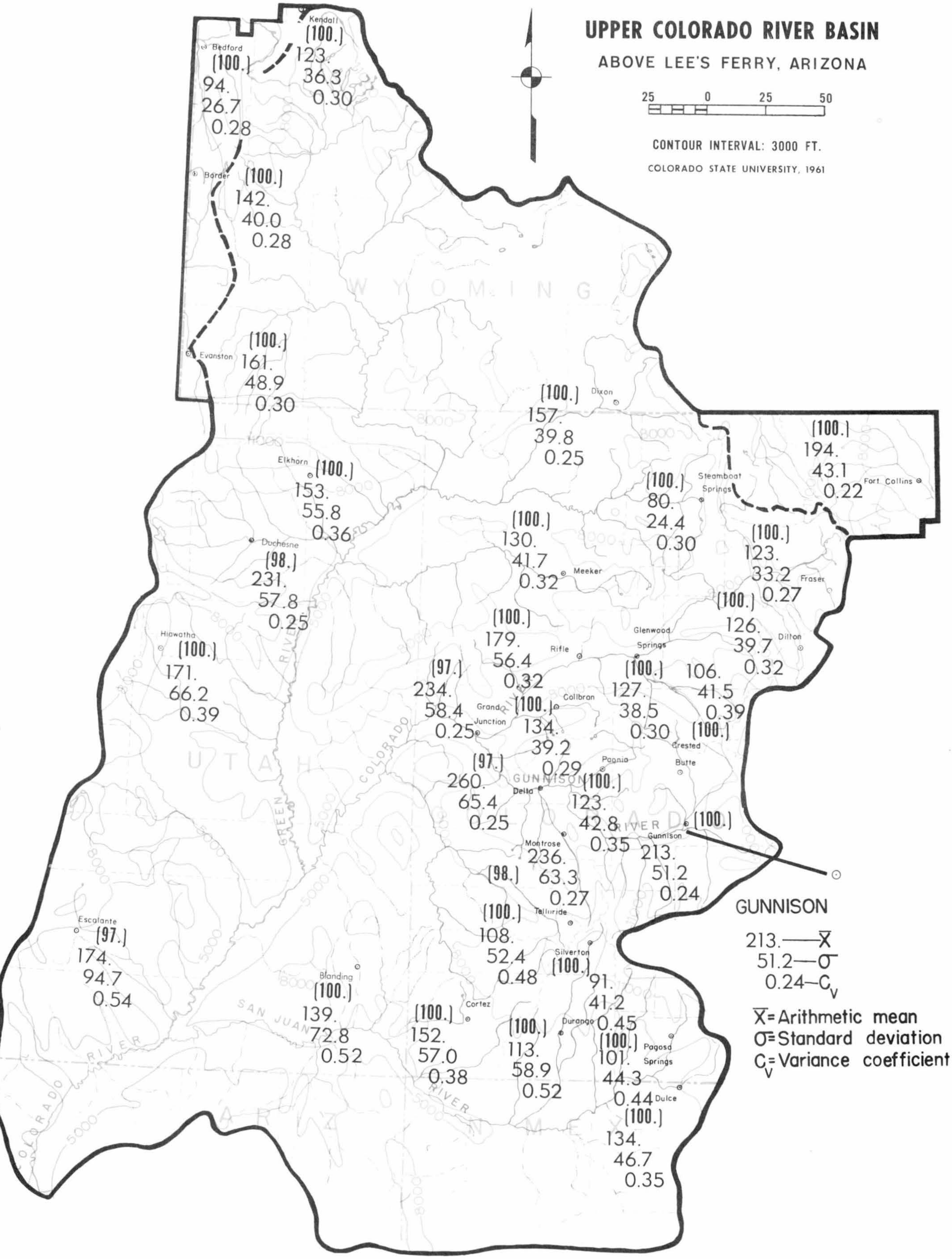


Fig. 10 Mean date, standard deviation in days, and coefficient of variation of acquiring 5 inches of precipitation during a water year. Number in parenthesis indicates the percent of total years of record in which 5 inches or more of precipitation was received.

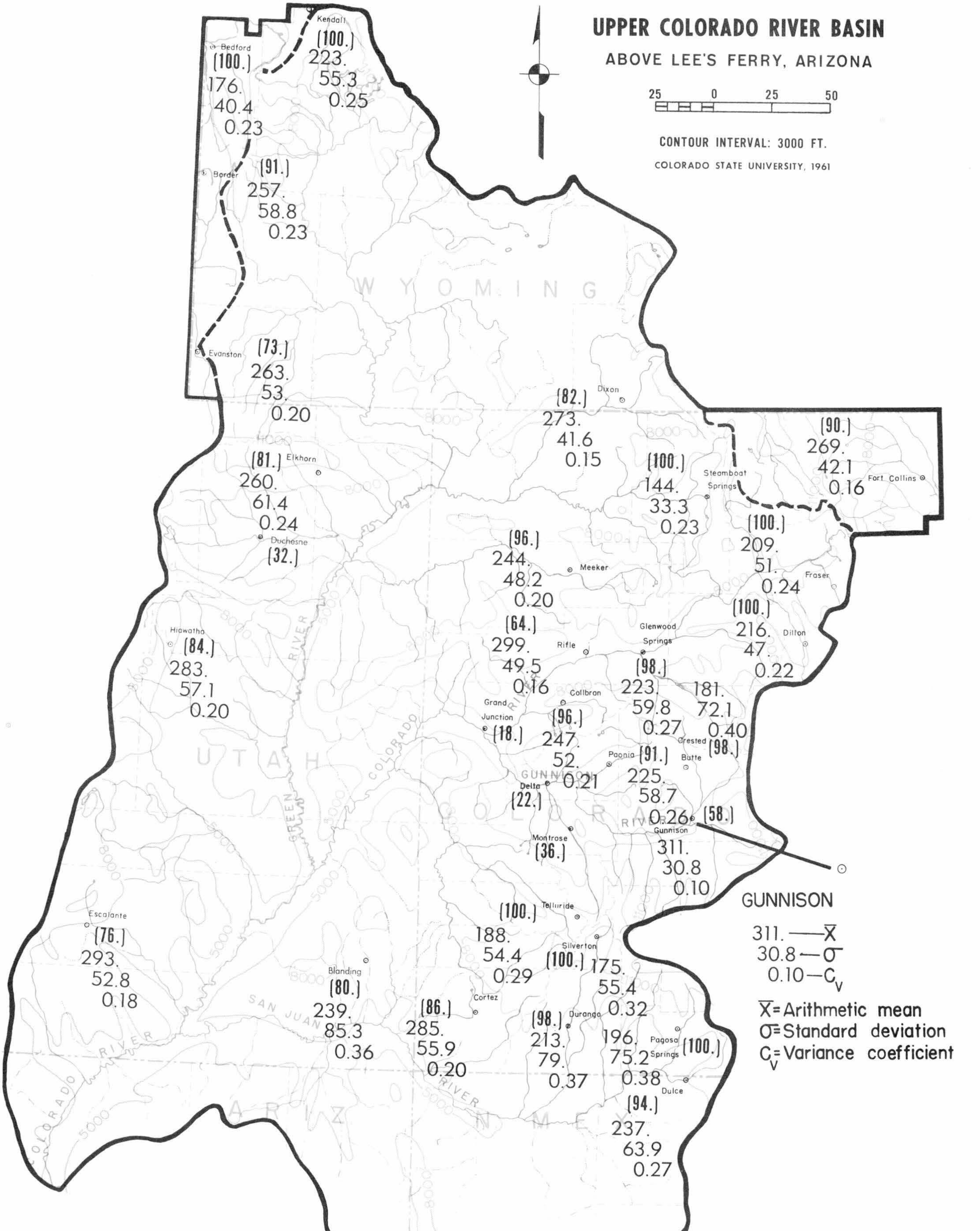


Fig. 11 Mean date, standard deviation in days, and coefficient of variation of acquiring 10 inches of precipitation during a water year. Number in parenthesis indicates the per cent of total years of record in which 10 inches or more of precipitation was received. Data are not shown when percentage is less than 50 per cent.

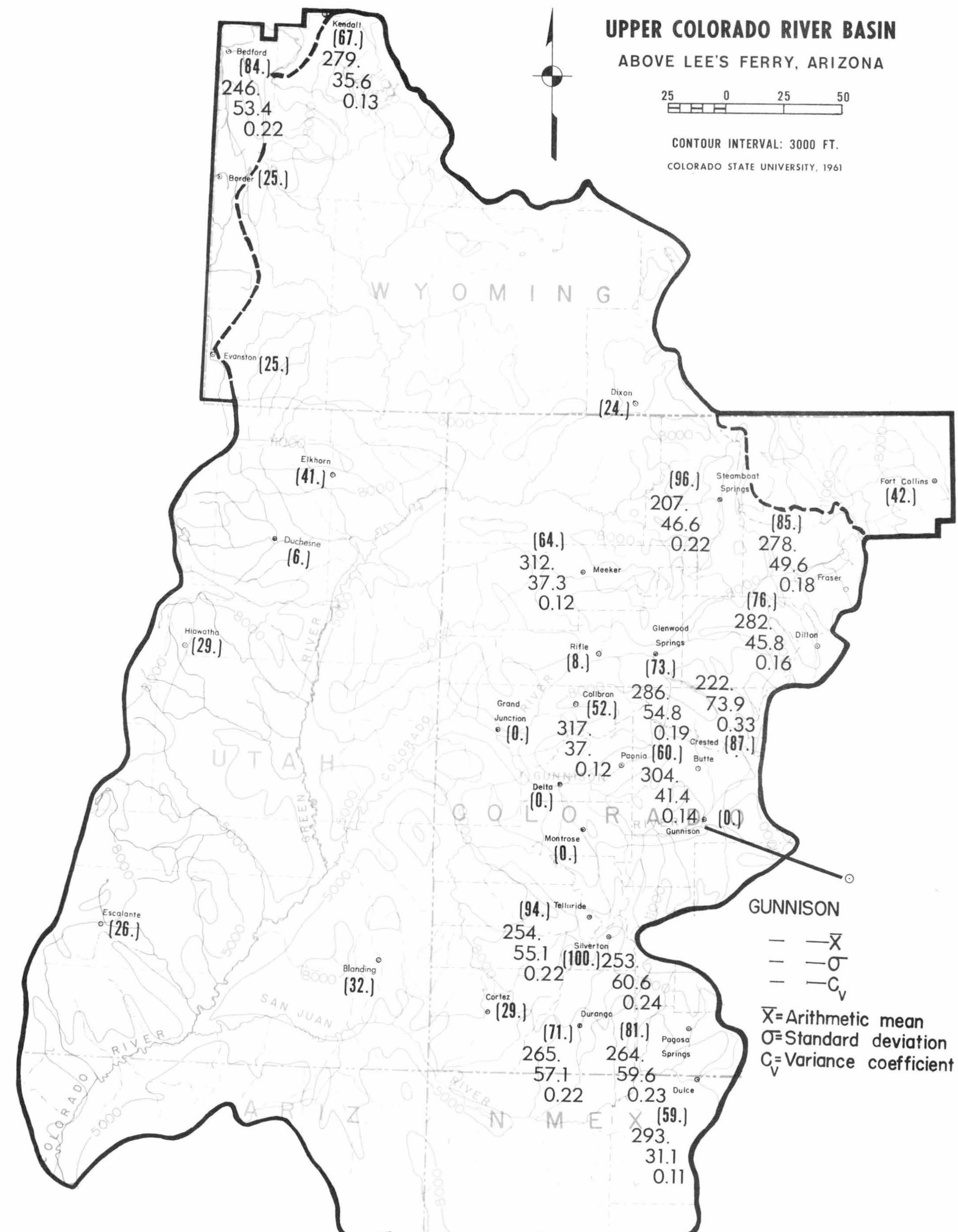


Fig. 12 Mean date, standard deviation in days, and coefficient of variation of acquiring 15 inches of precipitation during a water year. Number in parenthesis indicates the percent of total years of record in which 15 inches or more of precipitation was received. Data are not shown when percentage is less than 50 percent.

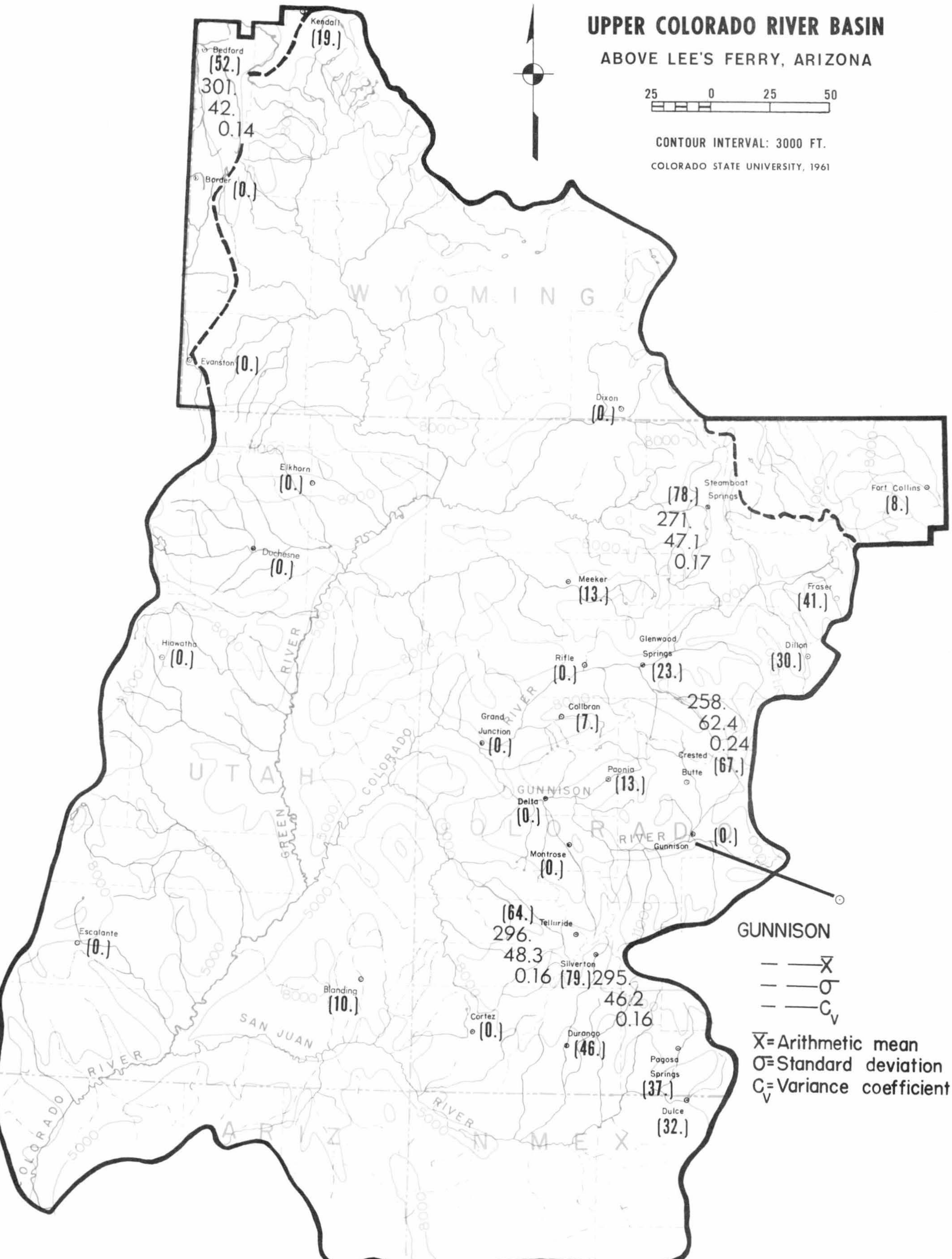


Fig. 13 Mean date, standard deviation in days, and coefficient of variation of acquiring 20 inches of precipitation during a water year. Number in parenthesis indicates the percent of total years of record in which 20 inches or more of precipitation was received. Data are not shown when percentage is less than 50 percent.

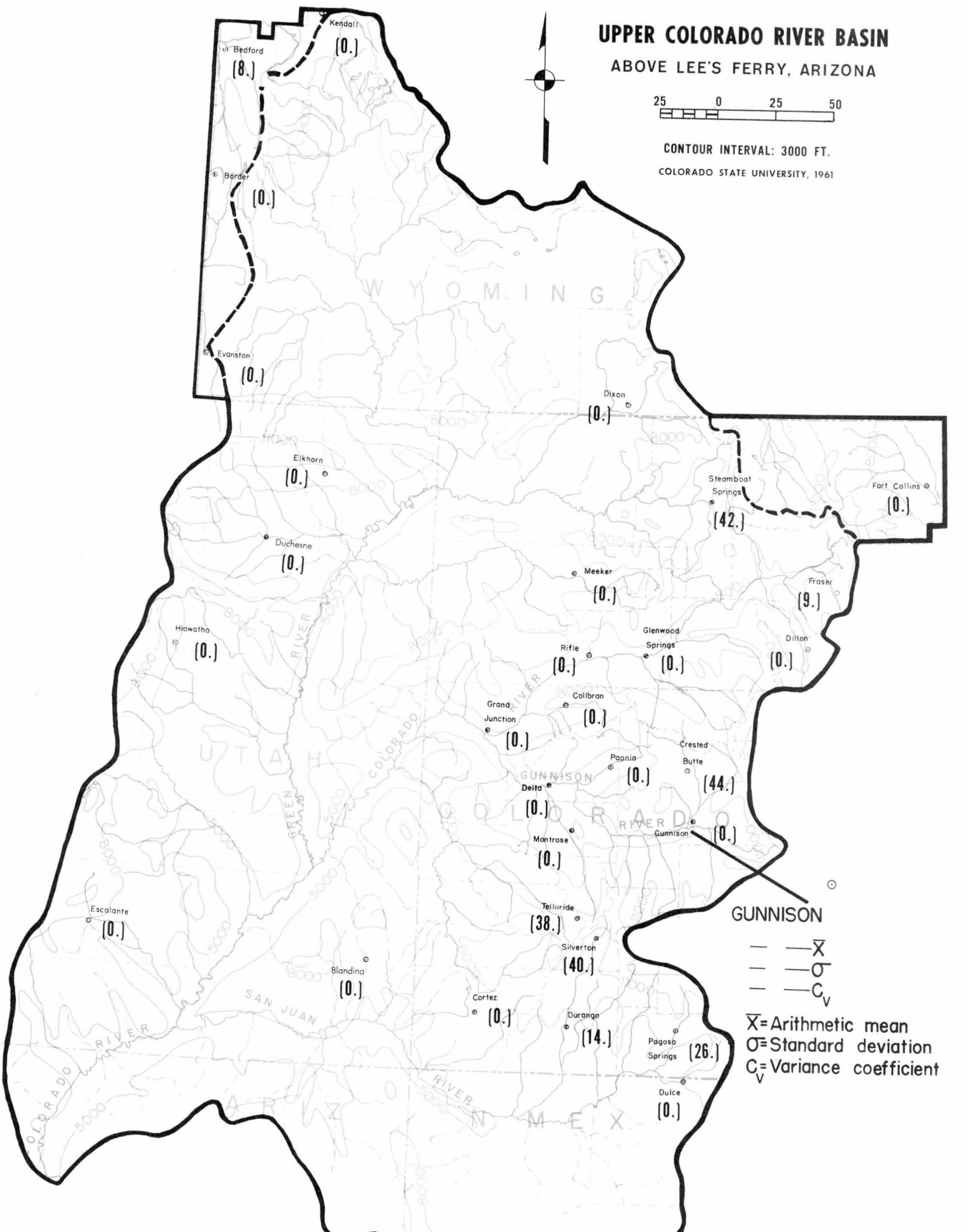


Fig. 14 Mean date, standard deviation in days, and coefficient of variation of acquiring 25 inches of precipitation during a water year. Number in parenthesis indicates the percent of total years of record in which 25 inches or more of precipitation was received. Data are not shown when percentage is less than 50 percent.

E. PROBABILITY OF RECEIVING GIVEN AMOUNTS (5, 10, 15, and 20 INCHES) OF PRECIPITATION DURING THE WATER YEAR AFTER 1 JANUARY, 1 MARCH, AND 1 MAY

1. Probability of Receiving More Than 5 Inches of Precipitation During the Balance of the Water Year

Figure 15 shows the probability of receiving more than 5 inches of precipitation during the water year after the calendar dates 1 January, 1 March, and 1 May. For example, the probability of Gunnison receiving more than 5 inches of precipitation after the first of January is 92.31 per cent, while the corresponding probability after 1 May is 59.62 per cent.

2. Probability of Receiving More Than 10 Inches of Precipitation During the Balance of the Water Year

Probability of receiving more than 10 inches of precipitation after the calendar dates of 1 January, 1 March, and 1 May are given in Figure 16. Figure 16 shows, for example, that the probability of receiving more than 10 inches of precipitation after 1 January for Gunnison is 26.92 per cent. The corresponding probabilities for Gunnison of receiving more than 10 inches of precipitation after 1 March and 1 May are 1.92, and 0 per cent respectively.

3. Probability of Receiving More Than 15 Inches of Precipitation During the Balance of the Water Year

The probabilities of receiving more than 15 inches of precipitation during the water year following 1 January, 1 March, and 1 May are given in Figure 17. Only for the higher altitude stations is there any significant probability of receiving more than 15 inches of precipitation in the water year following 1 January.

4. Probability of Receiving More Than 20 Inches of Precipitation During the Balance of the Water Year

For most of the stations in the Upper Colorado River Basin the probability of receiving more than 20 inches of precipitation after the 1st of May is zero. Only for Silverton is the probability greater than zero. For the rest of the stations in the Upper Colorado River Basin none of these years of record gave as much as 20 inches of precipitation during the water year after 1 May. (Figure 18).

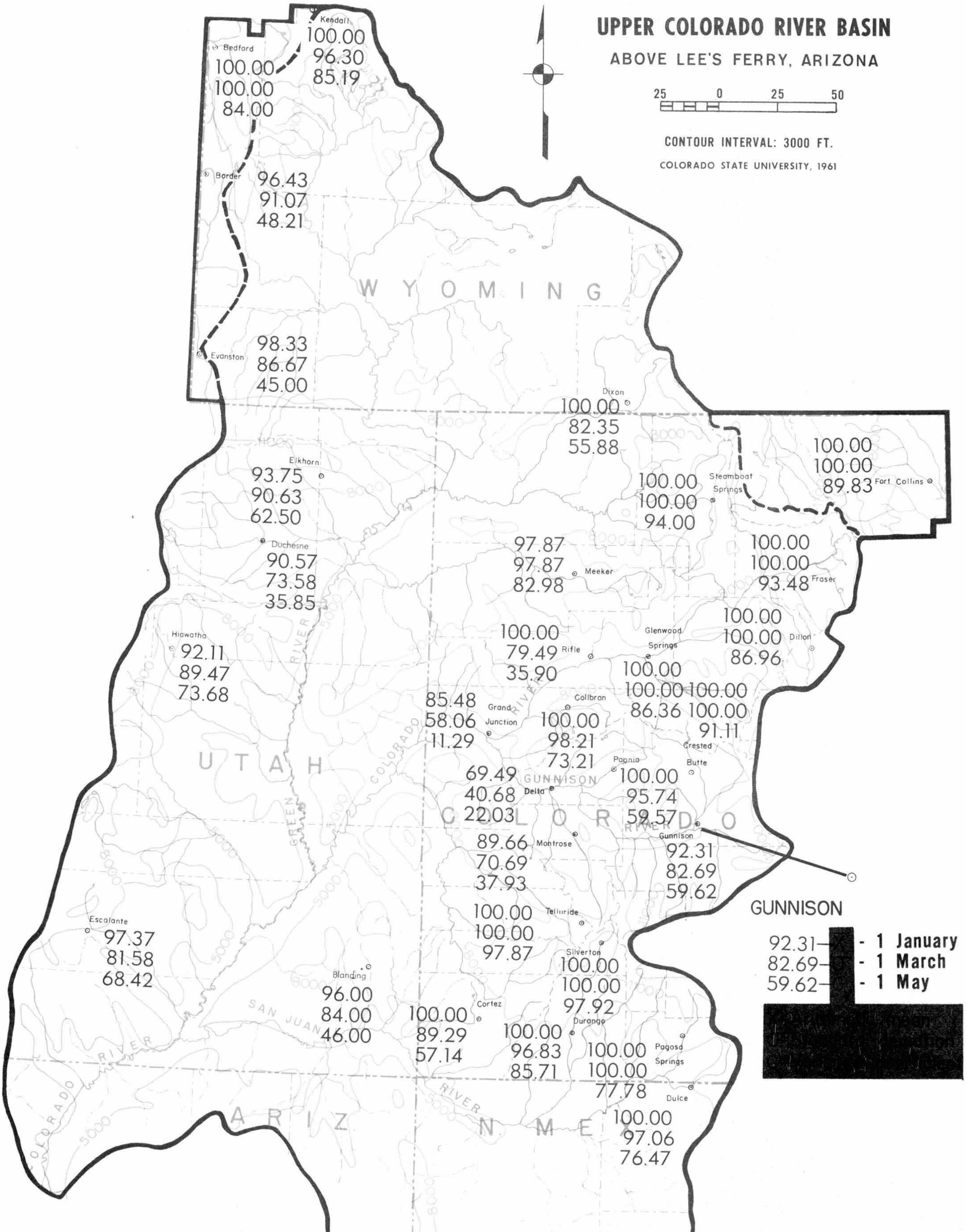


Fig. 15 Probability of receiving more than 5 inches of precipitation during the water year after 1 January, 1 March, and 1 May.

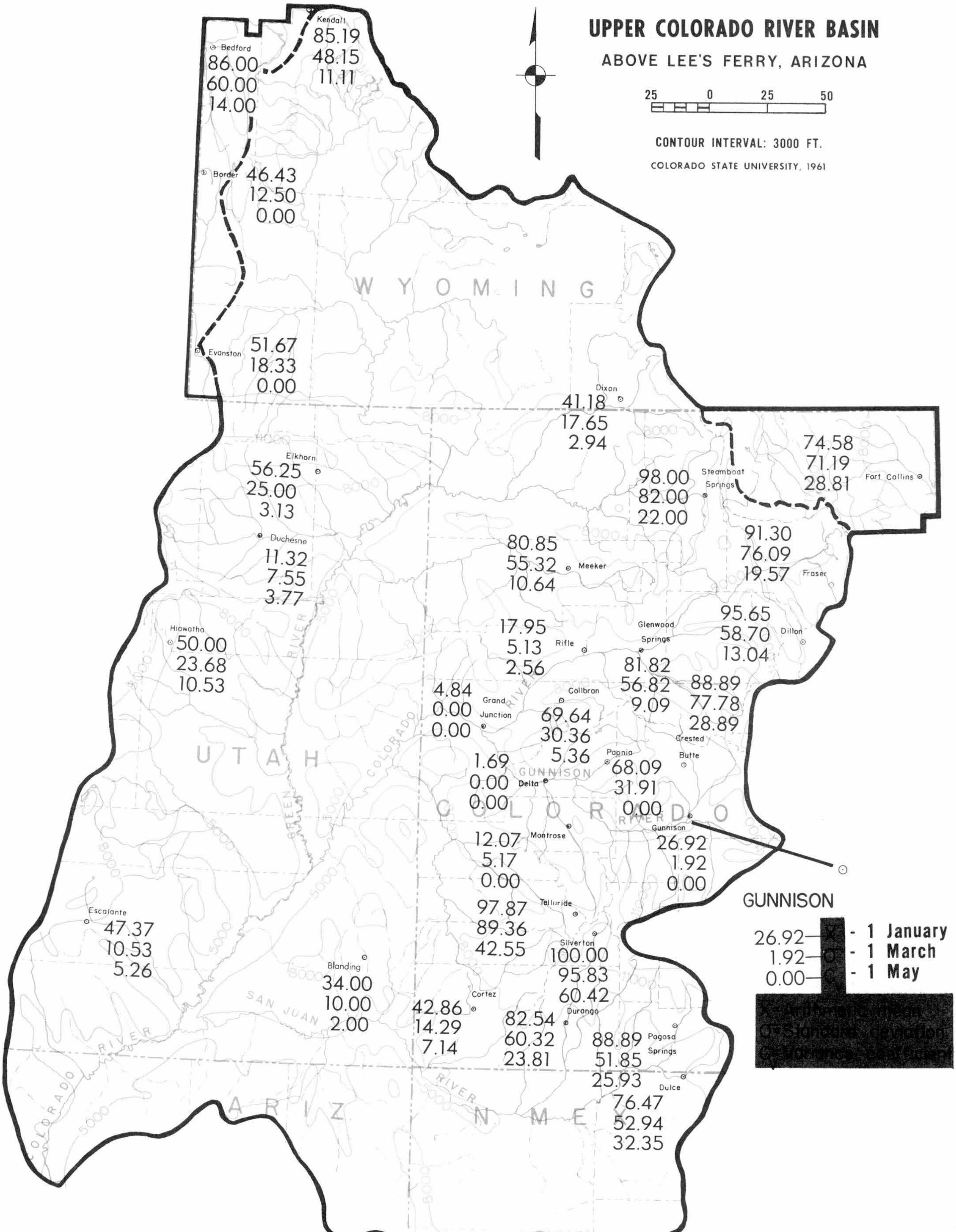


Fig. 16 Probability of receiving more than 10 inches of precipitation during the water year after 1 January, 1 March, and 1 May.

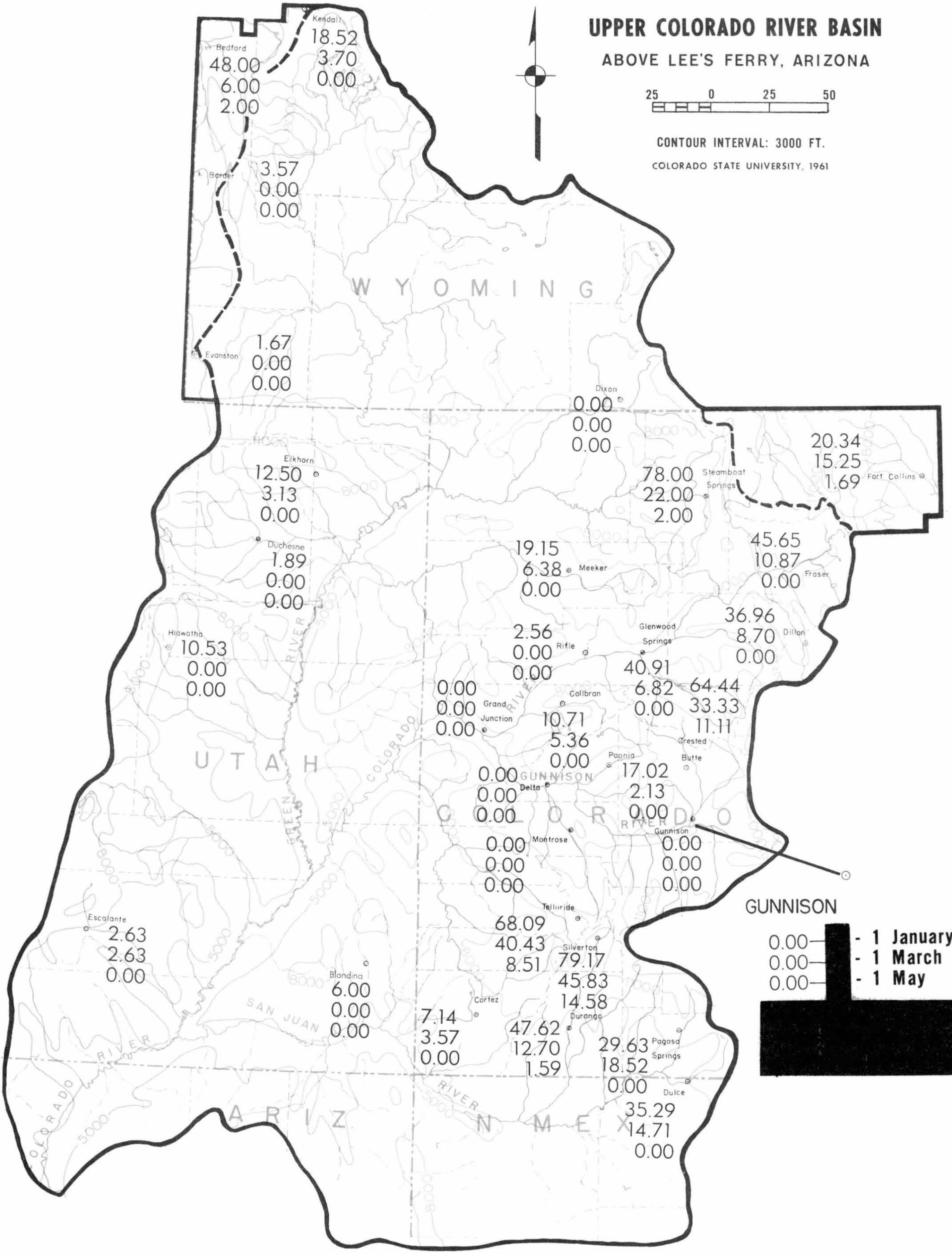


Fig. 17 Probability of receiving more than 15 inches of precipitation during the water year after 1 January, 1 March, and 1 May.

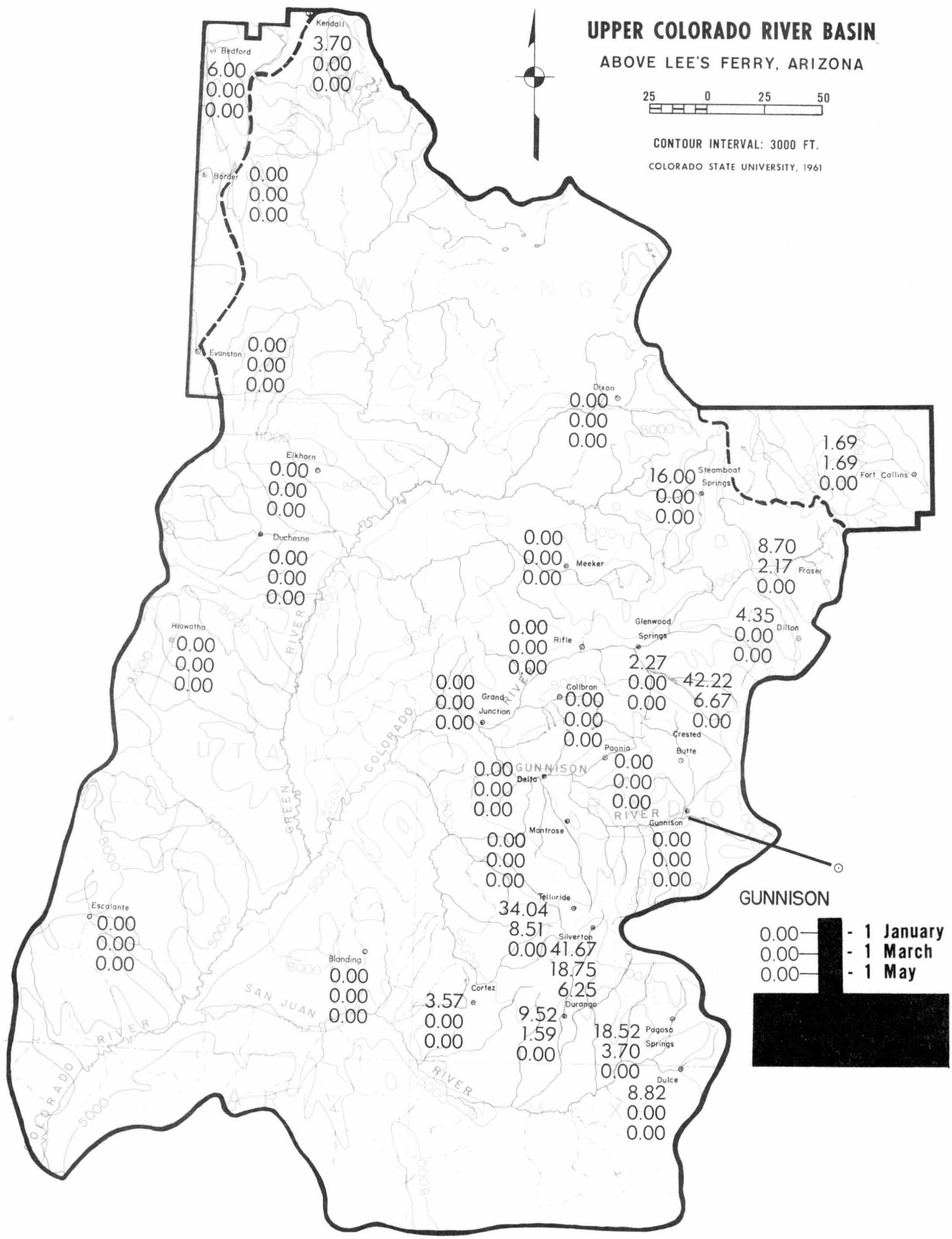


Fig. 18 Probability of receiving more than 20 inches of precipitation during the water year after 1 January, 1 March, and 1 May.

F. AMOUNTS OF PRECIPITATION RECEIVED FROM STORMS FOR THE VARIOUS MONTHS OF THE WATER YEAR, OCTOBER - SEPTEMBER

The probabilities of receiving various amounts of precipitation from storms beginning in various months of the water year are presented in Figures 19 through 30. These data correspond approximately to monthly precipitation amounts. They were computed by determining the frequencies of occurrence of precipitation from storms that begin in the particular month under consideration.

The precipitation from storms beginning in each month of the water year is shown in Figures 19 - 29. These precipitation amounts are highly variable as shown by the coefficients of variation that sometimes exceed unity. (For example, Fort Collins has a coefficient of variation of 1.29 as shown in Figure 21).

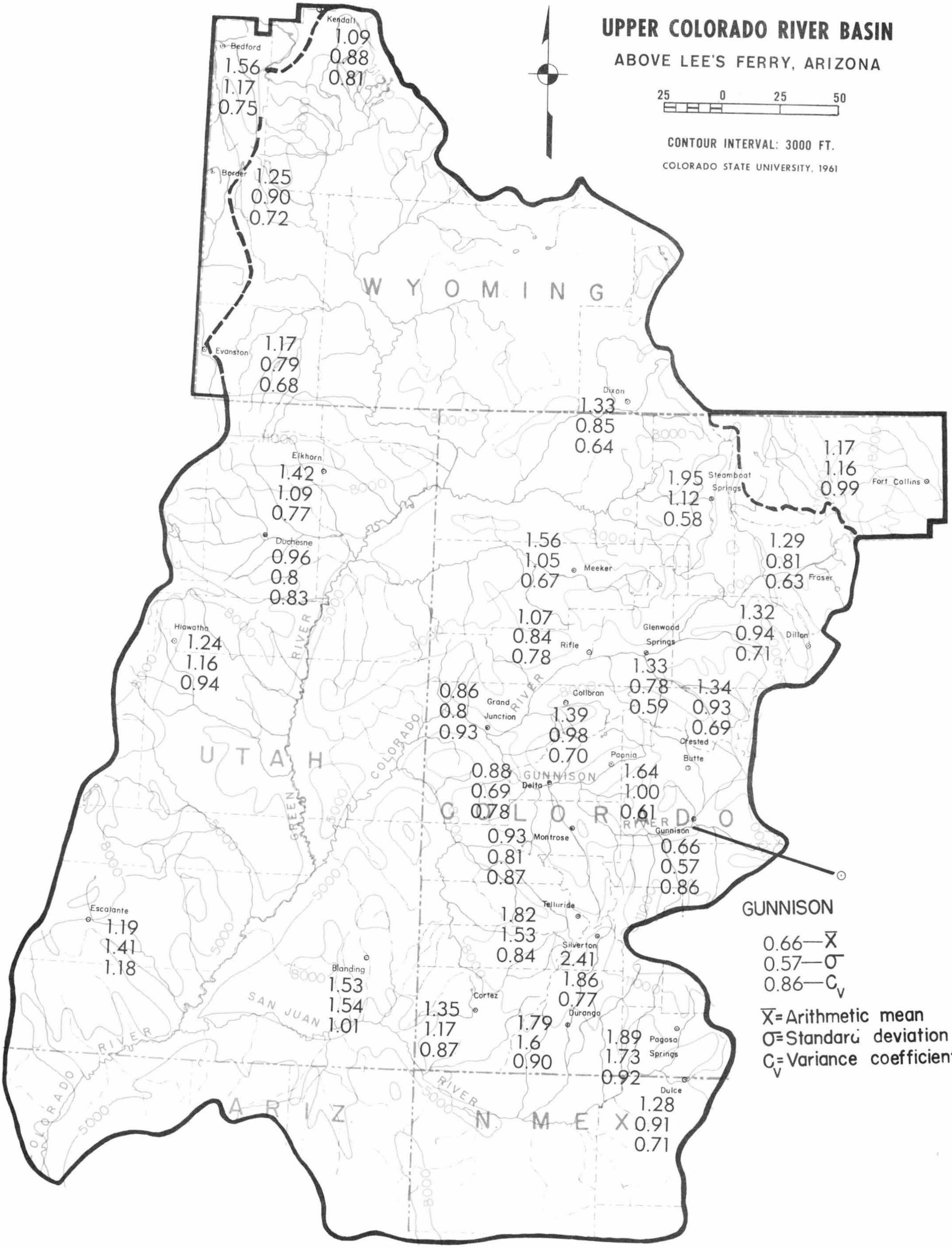


Fig. 19 Mean, standard deviation and coefficient of variation of the amount of precipitation (in inches) received from storms beginning in October.

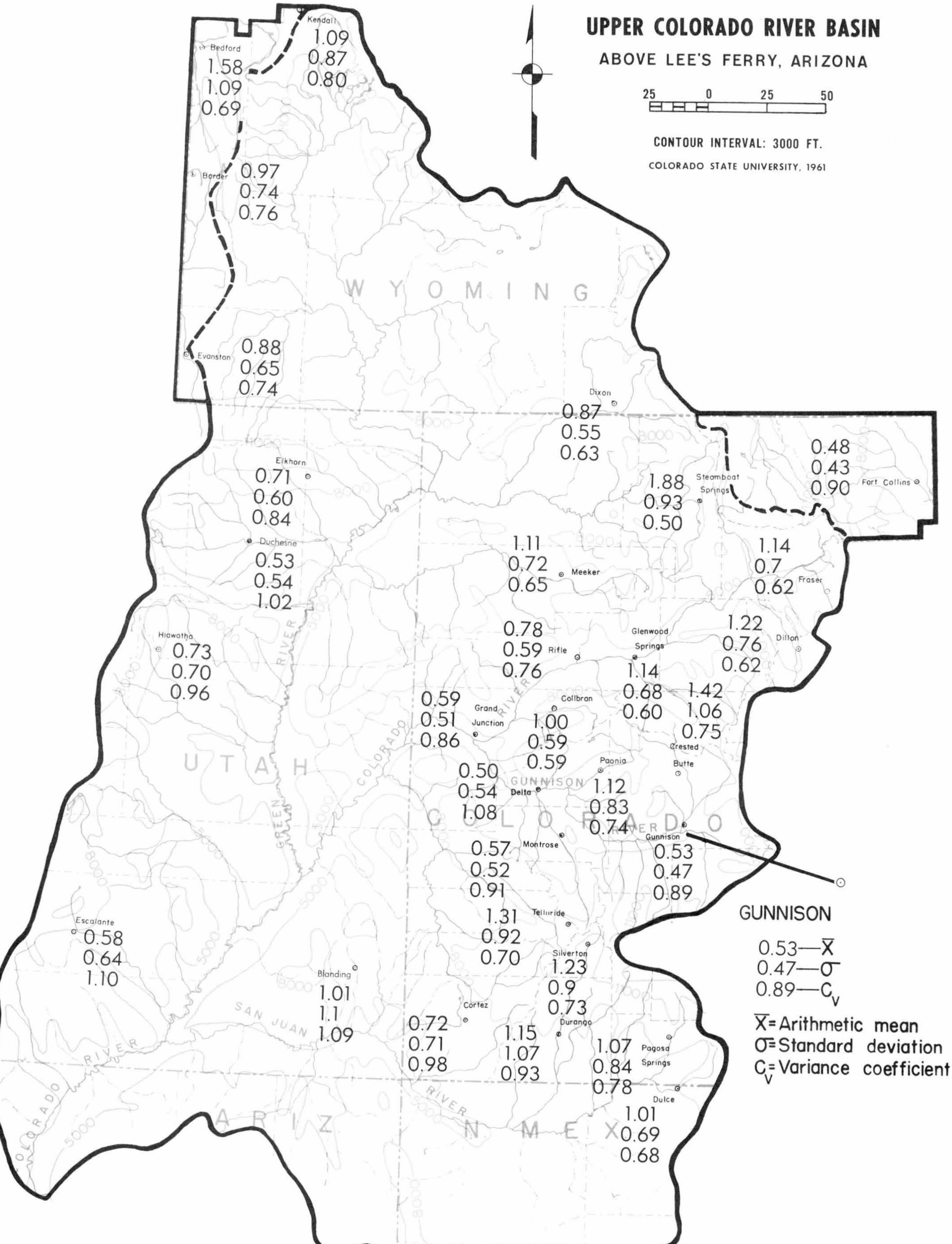


Fig. 20 Mean, standard deviation and coefficient of variation of the amount of precipitation (in inches) received from storms beginning in November.

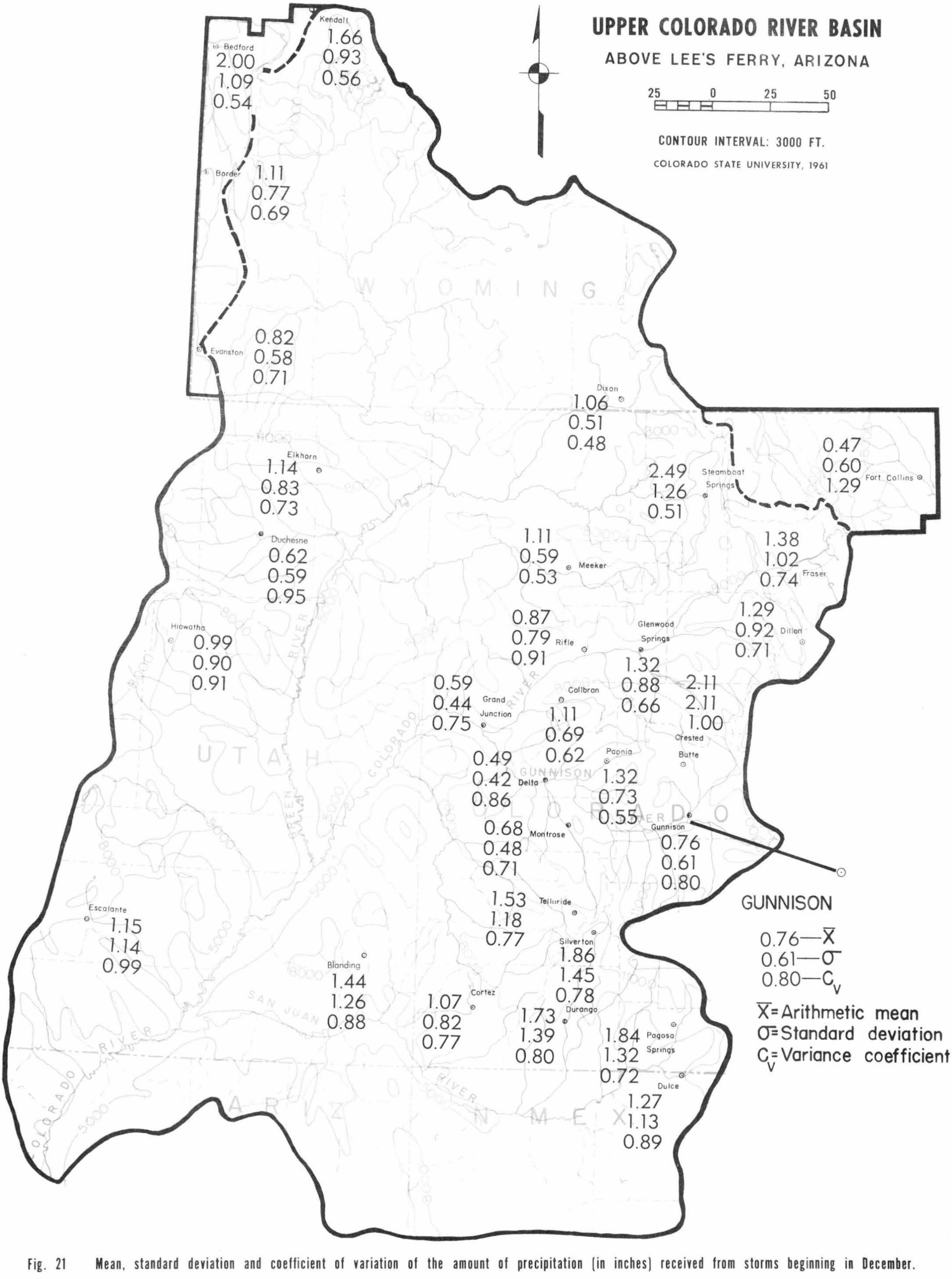


Fig. 21 Mean, standard deviation and coefficient of variation of the amount of precipitation (in inches) received from storms beginning in December.

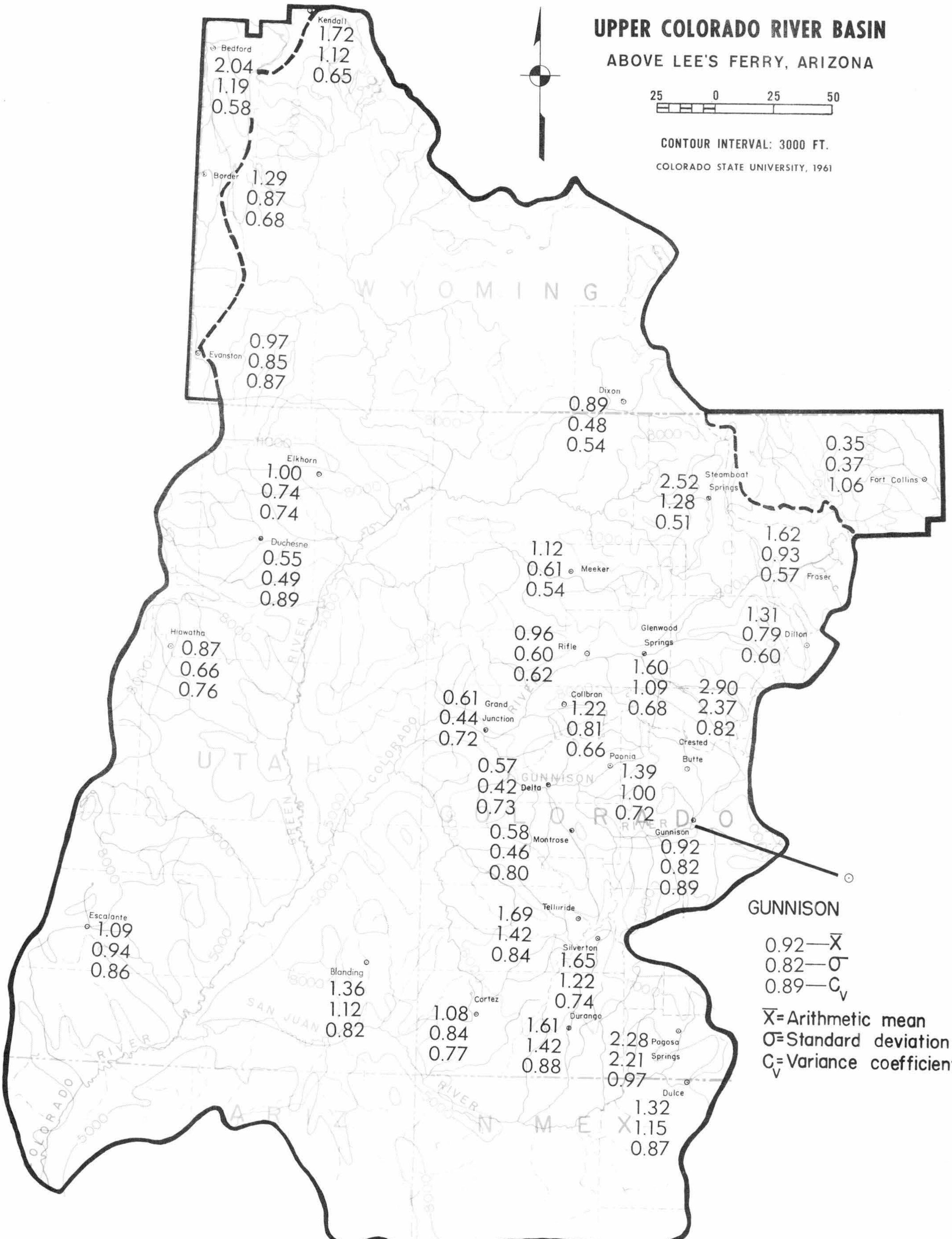


Fig. 22 Mean, standard deviation and coefficient of variation of the amount of precipitation (in inches) received from storms beginning in January.

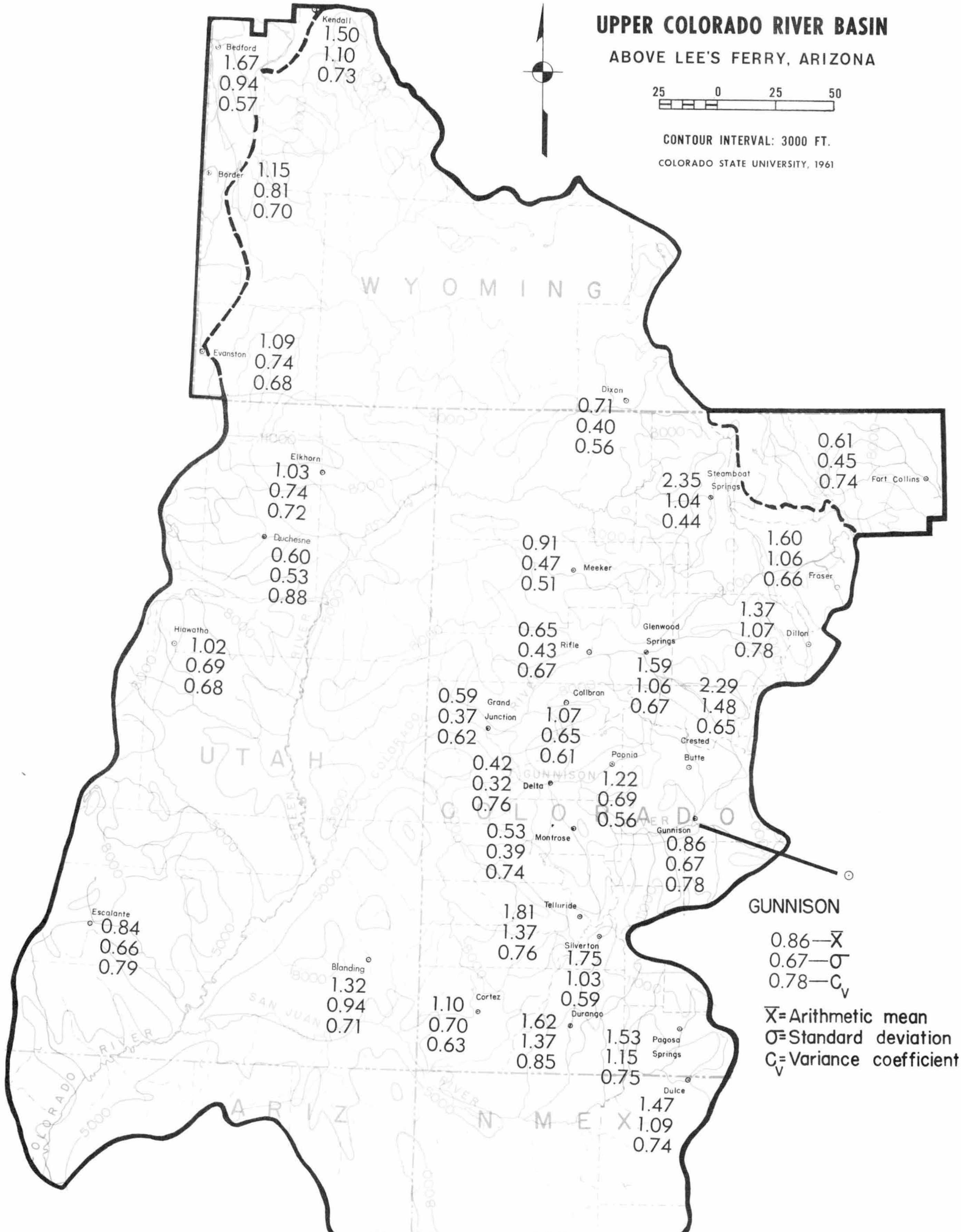


Fig. 23 Mean, standard deviation and coefficient of variation of the amount of precipitation (in inches) received from storms beginning in February.

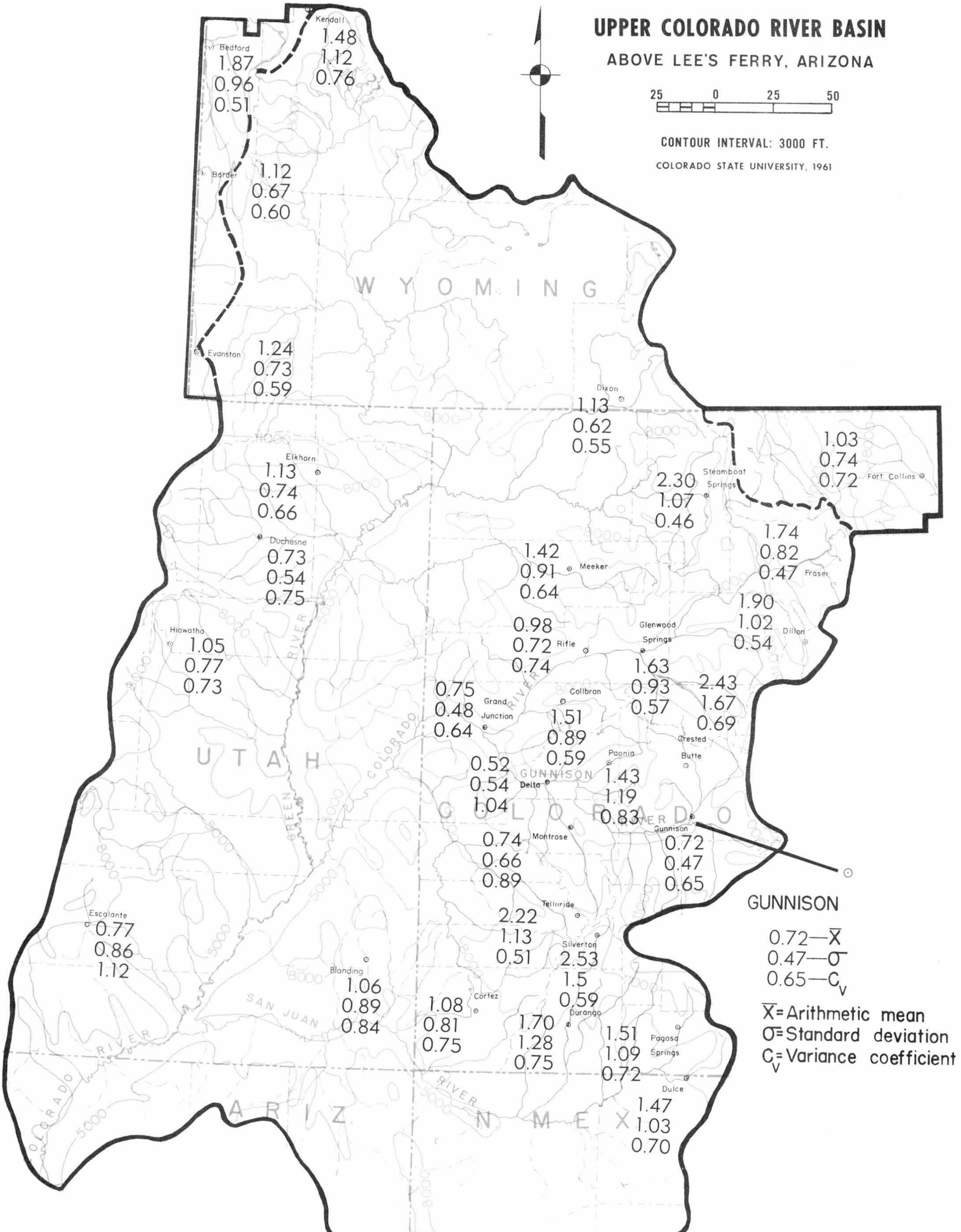


Fig. 24 Mean, standard deviation and coefficient of variation of the amount of precipitation (in inches) received from storms beginning in March.

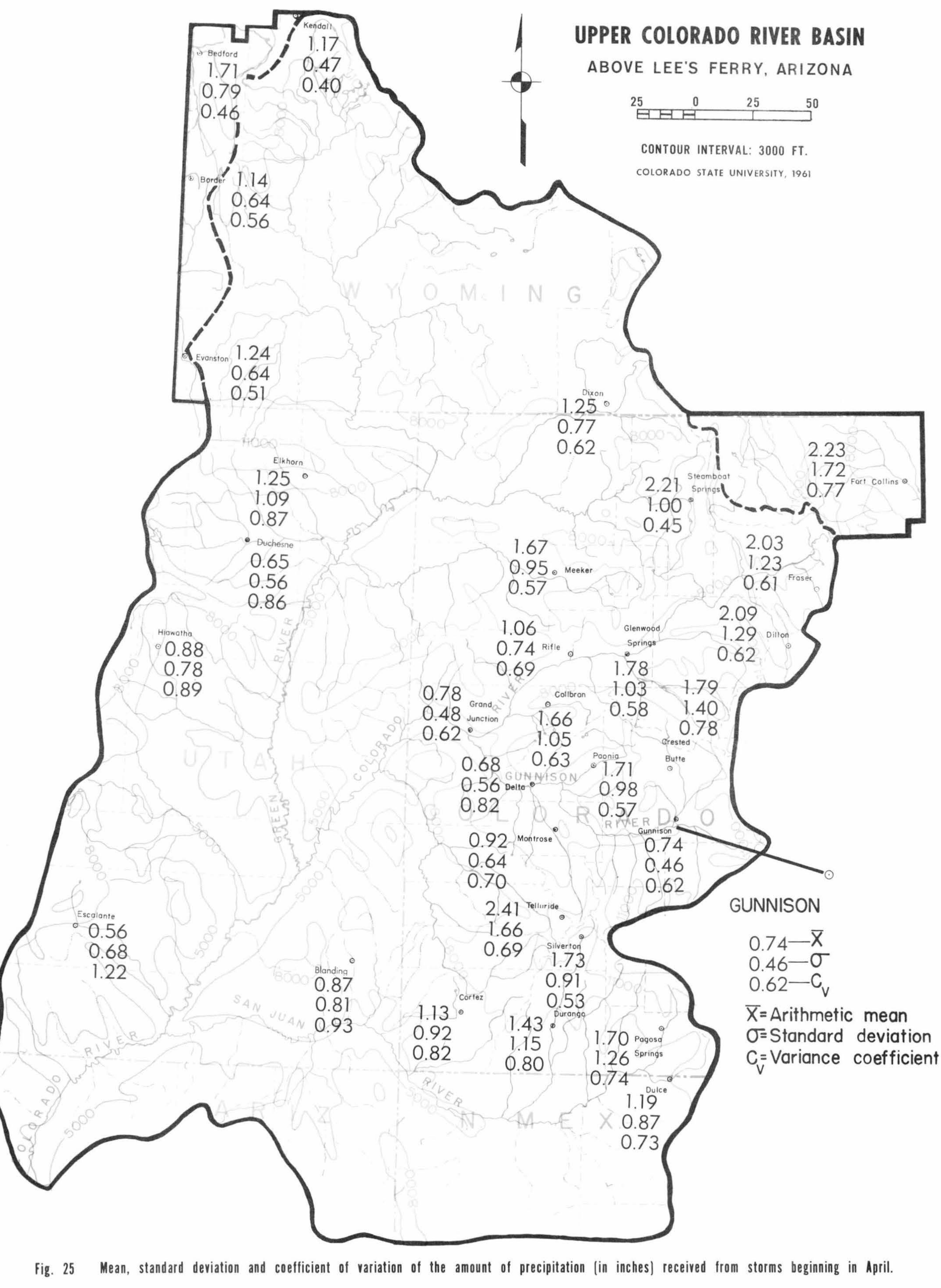


Fig. 25 Mean, standard deviation and coefficient of variation of the amount of precipitation (in inches) received from storms beginning in April.

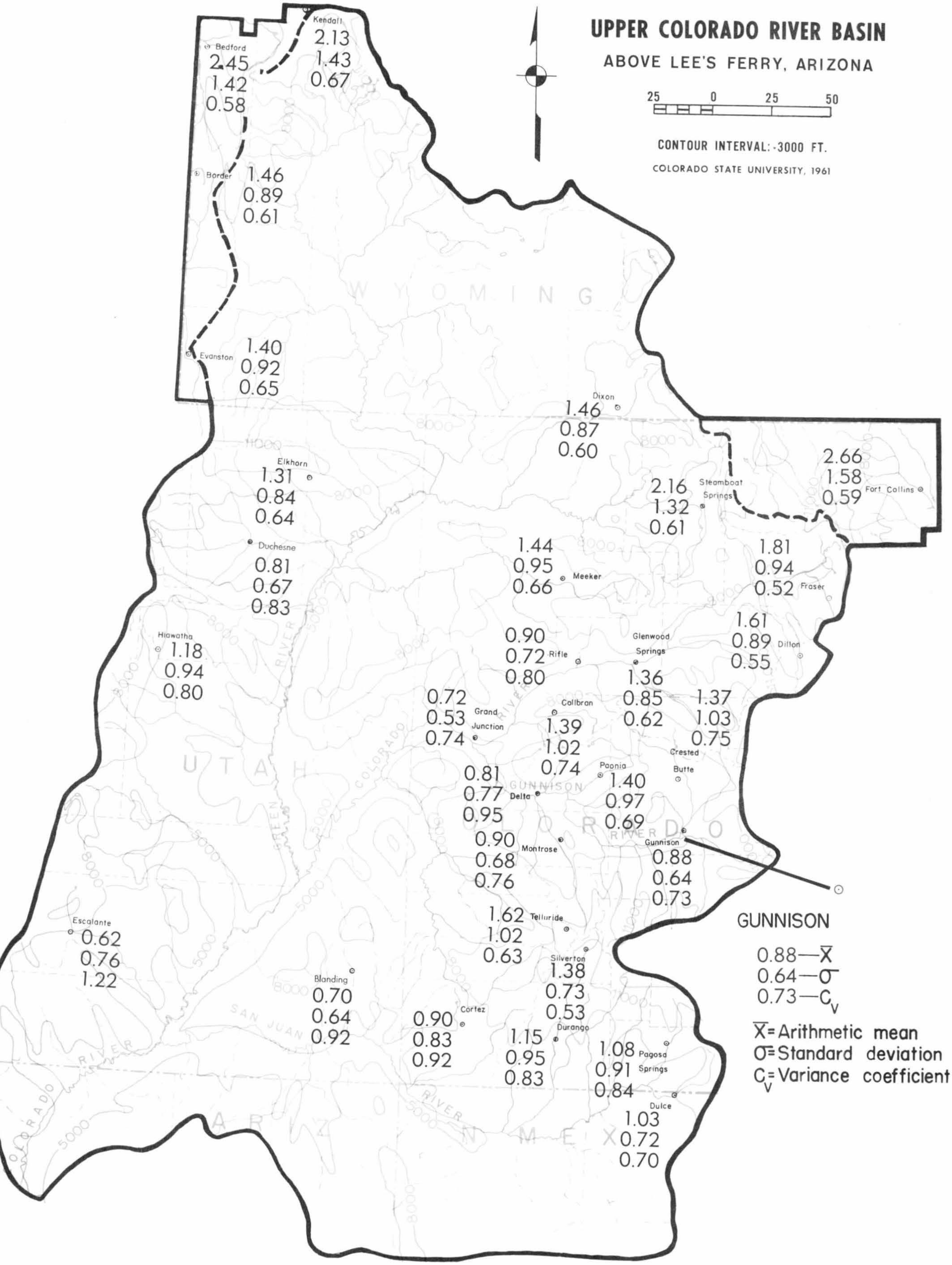


Fig. 26 Mean, standard deviation and coefficient of variation of the amount of precipitation (in inches) received from storms beginning in May.

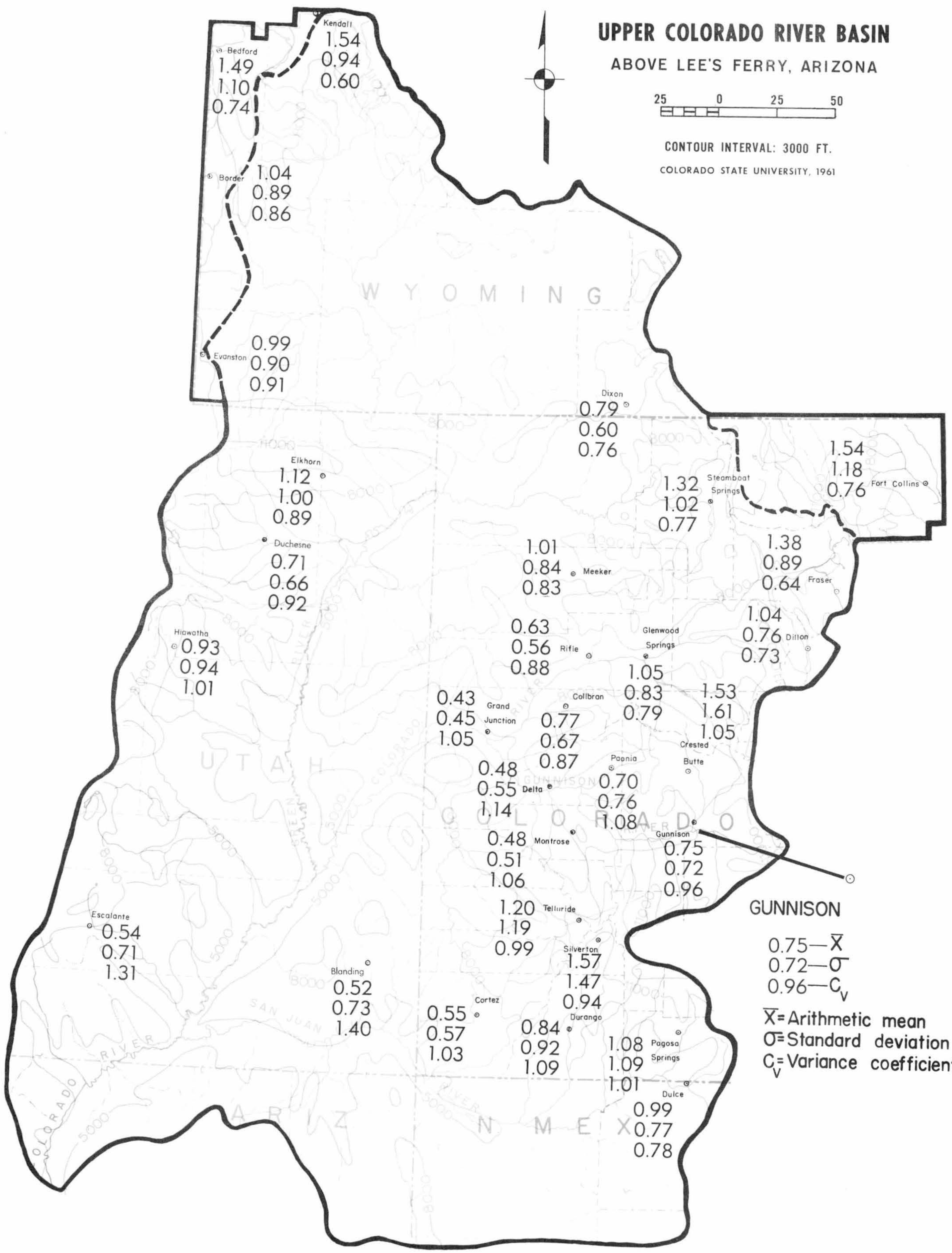


Fig. 27 Mean, standard deviation and coefficient of variation of the amount of precipitation (in inches) received from storms beginning in June.

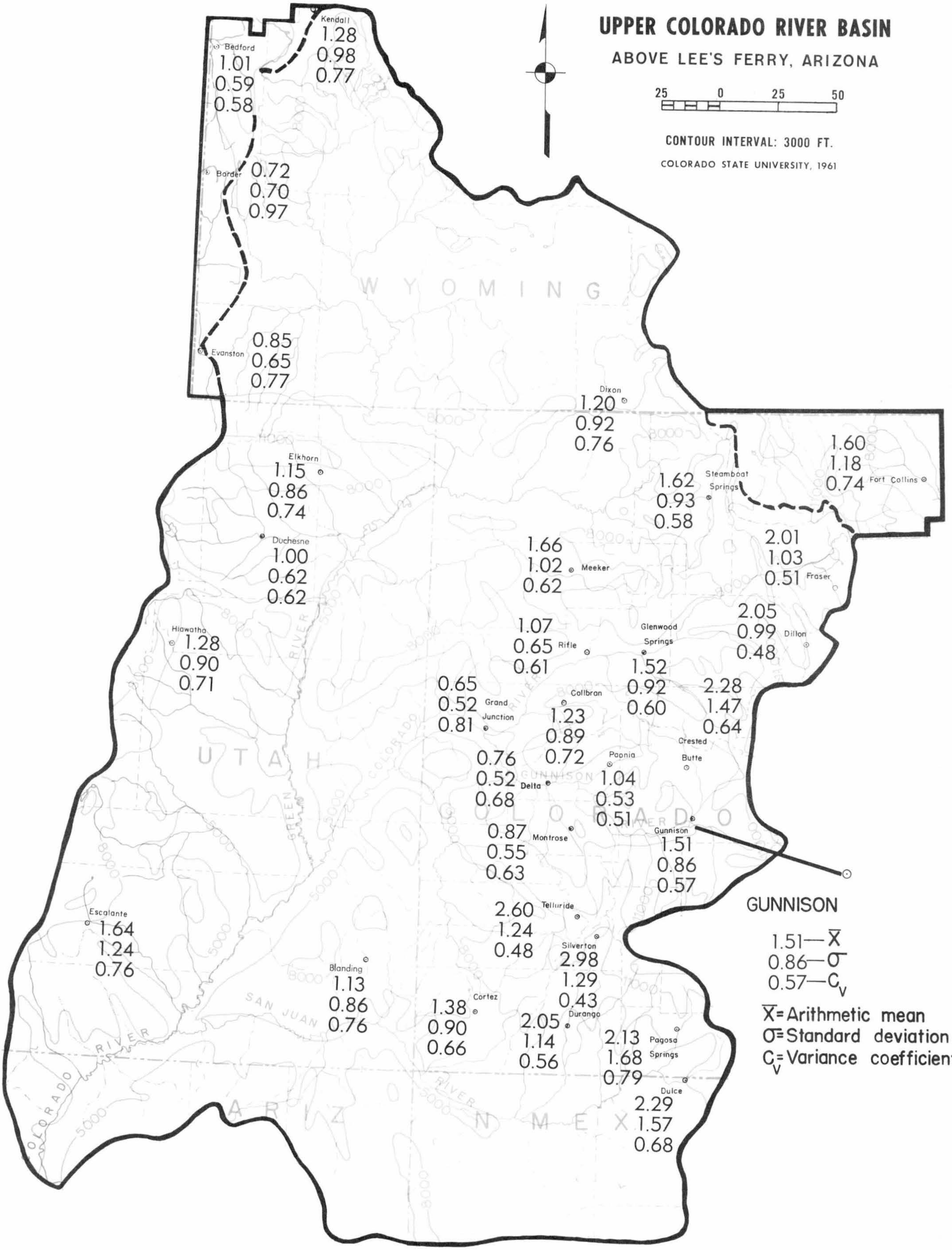


Fig. 28 Mean, standard deviation and coefficient of variation of the amount of precipitation (in inches) received from storms beginning in July.

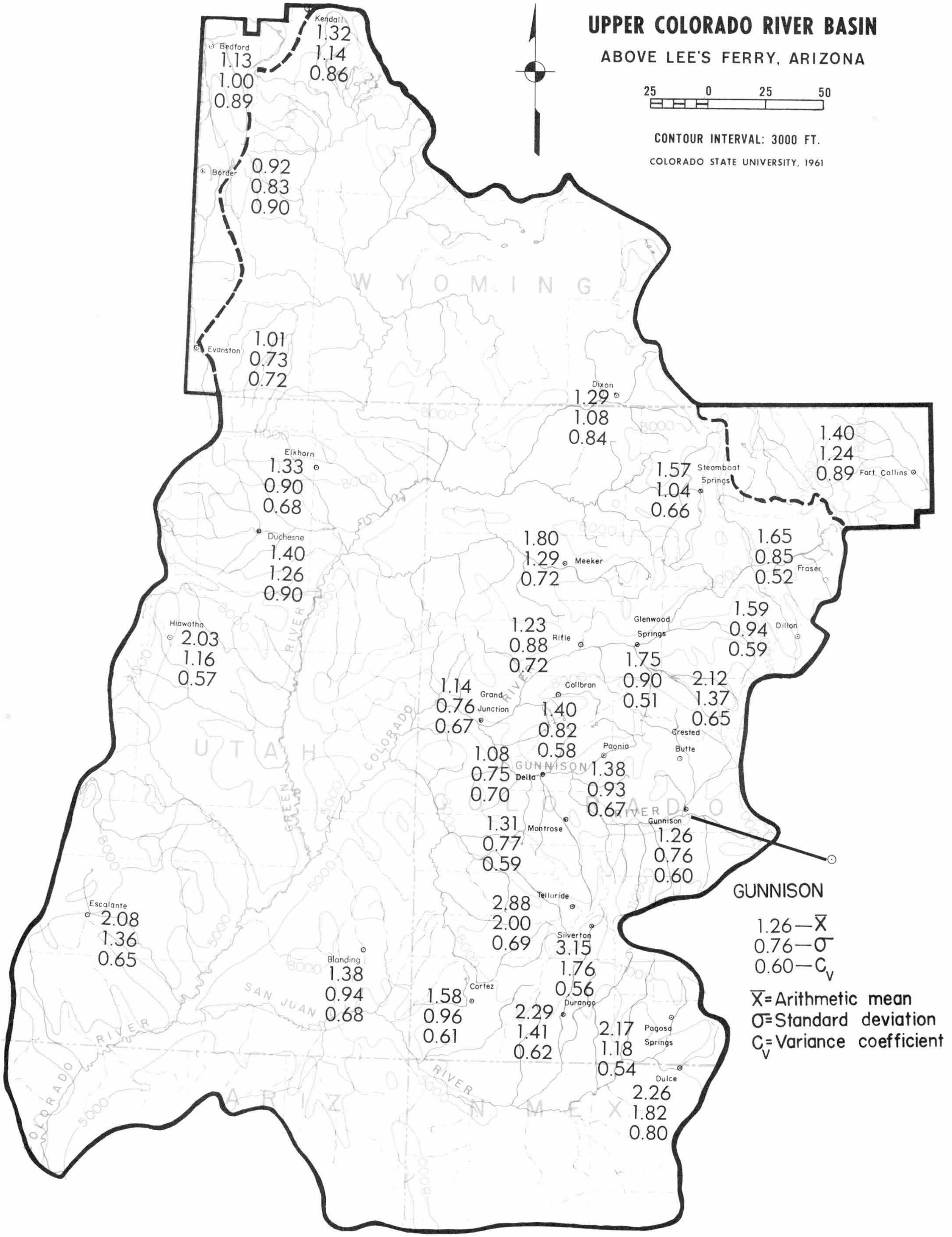


Fig. 29 Mean, standard deviation and coefficient of variation of the amount of precipitation (in inches) received from storms beginning in August.

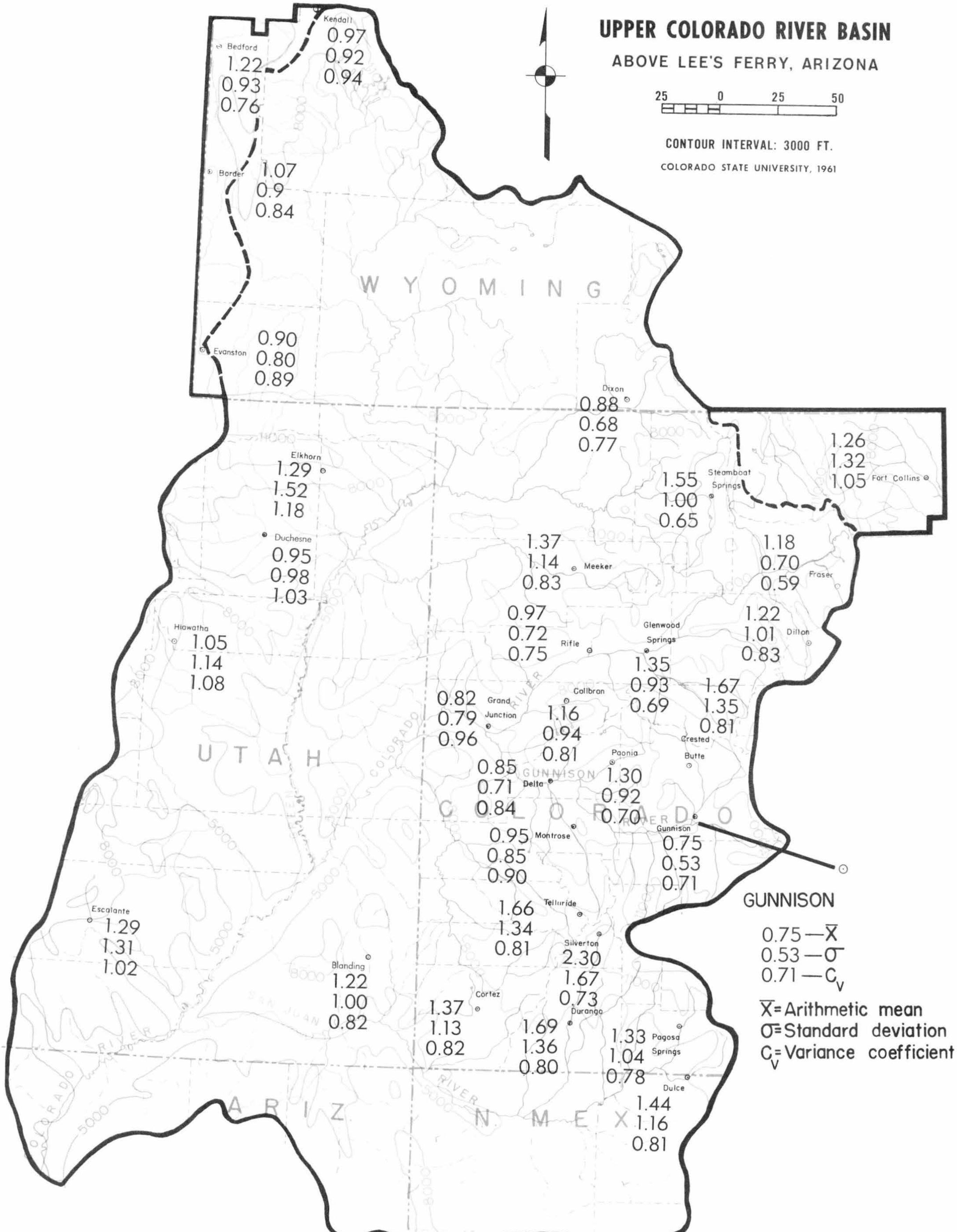


Fig. 30 Mean, standard deviation and coefficient of variation of the amount of precipitation (in inches) received from storms beginning in September.

G. DISTRIBUTION OF PRECIPITATION DURING THE WATER YEAR

It will be noted from Figure 31 that the mean value of the precipitation received in each of the months of the water year is higher than the corresponding median value. (See also Table IV).

The distribution of precipitation within the water year may be seen in Figure 31. For example, stations in the southern part of the basin such as Escalante and Montrose receive a major portion of their annual precipitation in August, September, and October and are relatively dry in the winter months. In contrast, high-altitude stations such as Steamboat Springs and also stations in Northern Wyoming such as Bedford and Border receive major amounts of precipitation during the winter season.

There is a marked contrast for Fort Collins, a station on the eastern slope of the Continental Divide. For Fort Collins the major precipitation amounts are received in the spring months of April and May.

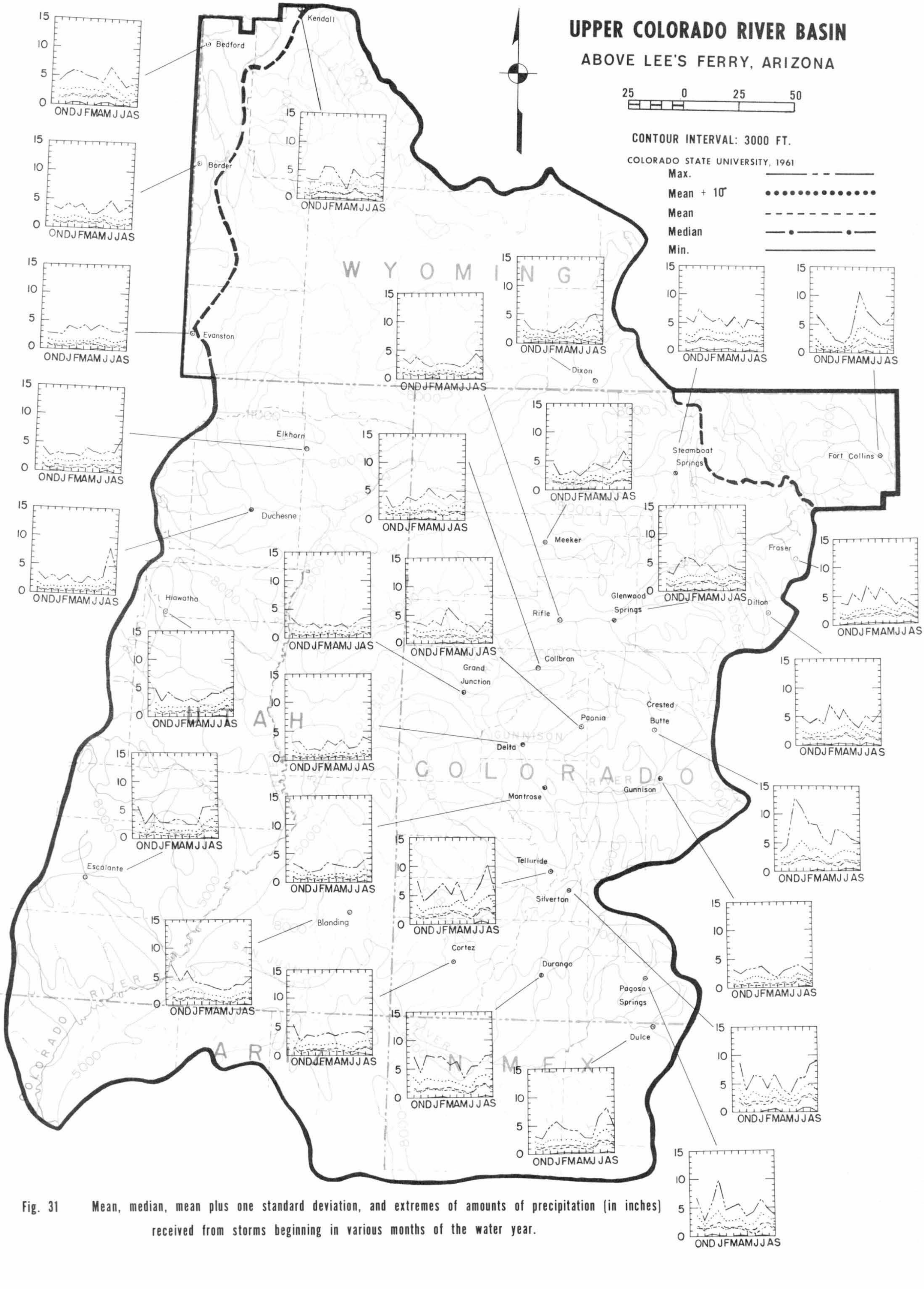


Fig. 31 Mean, median, mean plus one standard deviation, and extremes of amounts of precipitation (in inches) received from storms beginning in various months of the water year.

H. FREQUENCY DISTRIBUTION OF PRECIPITATION AMOUNTS

Figure 32 shows the frequency distribution of precipitation for two individual months and for the year, based on the period of record at each station. These frequency distributions are to be read as indicating the amounts of precipitation "equal to or less than." For example, about 10.5 inches of precipitation or less was received 50 per cent of the time during the water year at Gunnison.

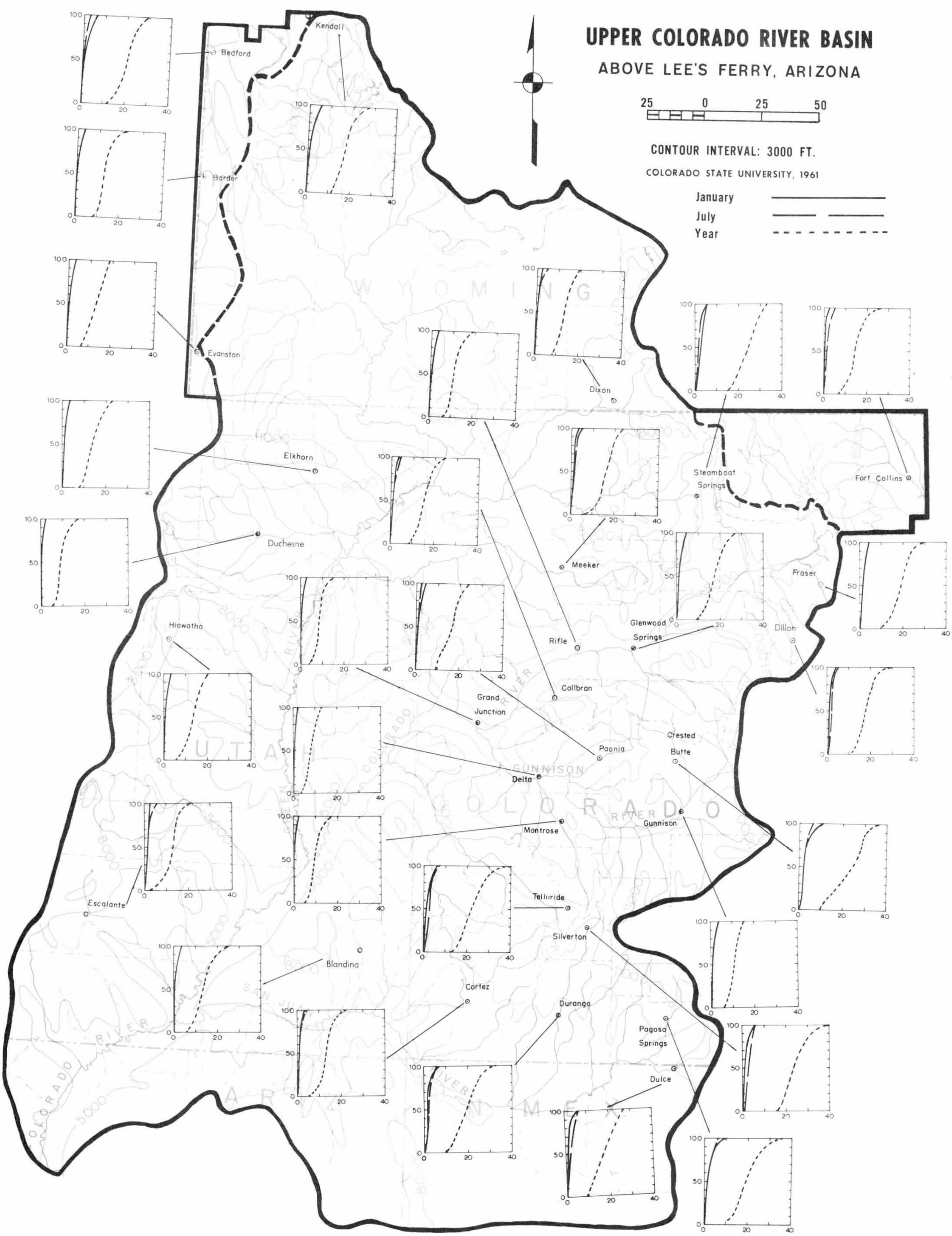


Fig. 32 Frequency distribution of precipitation amounts received for the entire water year, and for storms beginning in January and July.

I. EXAMPLE OF CORRELATION STUDY BY MACHINE TABULATION PROCEDURE

Precipitation data from Delta, Gunnison and Crested Butte were used in a study to attempt to derive forecasting equations for seasonal runoff (April - July) for the Gunnison River above Gunnison Tunnel. In making this study it was recognized that the runoff from the Gunnison River was dependent upon factors other than precipitation alone. No attempt was made to "weight" the precipitation according to elevation or area.

1. Objective

The purpose of the study was:

a. To attempt to develop forecasting equations for seasonal runoff for the Gunnison River.

b. To attempt to develop procedures and techniques to be followed using a "refined" climatological precipitation data as developed in this study.

c. To deduce certain physical facts regarding the mechanisms affecting runoff on the Gunnison River.

2. Procedure

The procedure for this study was as follows: The seasonal runoff of the Gunnison River was correlated with precipitation from three stations, Delta, Gunnison, and Crested Butte (stations located in and near the Gunnison River drainage area). The following combinations were used. Combinations of stations:

Delta, a low elevation station - L
Gunnison, a middle level elevation station - M
Crested Butte, a high elevation station - H.

All possible combinations of stations, L, M, and H, LM, MH, LH and LMH were used for a total of seven combinations.

Five estimates of evapotranspiration were used. This first estimate, evapotranspiration estimate A, was the observed precipitation without any deductions for evapotranspiration. Evapotranspiration estimate B was the same as given in Table III in this report. Evapotranspiration estimate C was obtained by subtracting 0.10 of an inch more per storm than the estimates given in Table III. Evapotranspiration estimate D was obtained by subtracting 0.10 of an inch less per storm than the amounts shown in Table III. Evapotranspiration estimate E was obtained by subtracting 0.20 of an inch more per storm for the low level station, 0.10 of an inch more per storm for the middle level station and subtracting the same amount for the high level station as the amounts shown in Table III.

A total of 34 precipitation periods were analyzed. Period one was to correlate October precipitation only with the following seasonal runoff. Precipitation period two was to use the sum of October plus November. Precipitation period three was to use October plus November plus December, etc. until we get to period ten which was the summation of October plus November--plus July correlated with the seasonal runoff. Periods 11 through 19 used November alone for period 11, November plus December for period 12, etc. until we get to precipitation period 19, which was the sum of all months, November through July.

Precipitation period 20 was December alone, precipitation period 21 was December plus January, etc. until we get to precipitation period 27 which was the sum of December plus January plus all months through July.

In a similar manner, precipitation periods 28 through 34 were for January through July.

The variables used were five evapotranspiration estimates, seven station combinations and 34 precipitation periods. The product of $7 \times 5 \times 34 = 1190$ separate combinations.

3. Results

For each of these 1190 separate computations the following information was obtained:

Equations of the form $Y = B_0 + B_1X_1$ were obtained for single stations.

Equations of the form $Y = B_0 + B_1X_1 + B_2X_2$ were obtained for two stations.

Equations of the form $Y = B_1 + B_1X_1 + B_1X_2 + B_3X_3$ were obtained for three stations. Where

Y = seasonal runoff, April through July.
X_1, X_2, X_3 = precipitation amounts from the three stations.

In addition, the correlation coefficient, the constants B_0, B_1, B_2, B_3, the standard error of estimate of Y, and the standard error of estimate for the individual regression coefficients were obtained.

4. Discussion

The details of this study are too lengthy to be included in this report. However, the following highlights of this study are worth mentioning here:

a. Individual correlation coefficients of up to approximately 0.6 were obtained.

b. Correlation coefficients for precipitation period No. 1 (October precipitation only) were generally higher than the values for later periods. This fact lends credence to the major storm concept discussed in greater detail in a later section of this report.

c. Correlation coefficients were such that it appears that the evapotranspiration estimates shown in Table III are probably slightly higher than actual values. A computation of the type described in this Gunnison River study would enable one to make better estimates of this evapotranspiration loss by repeated estimates of the type described in this study.

d. Correlation coefficients obtained for precipitation periods extending through April were usually better than for periods including precipitation from months following April. The reason for this fact is not known. It suggests, however, that forecasts of runoff from the Gunnison River may be of acceptable quality if prepared at the time the winter precipitation data are available for April, without being concerned about the additional amounts of precipitation that may fall later in the season on the Basin.

e. This preliminary study illustrates one of the procedures that might be followed in adapting "refined" climatological data to hydrologic problems of an operational nature. Better results would be anticipated in smaller catchment areas.

III. A REVIEW OF MAJOR STORMS WHICH HAVE OCCURRED IN THE UPPER COLORADO RIVER BASIN*

A. OBJECTIVES

While reviewing the actual sequence of precipitation amounts recorded at each of 18 stations in Western Colorado during a 46-year sample, it was noted that on rather rare occasions heavy precipitation amounts occurred simultaneously at many stations. A very cursory investigation showed that the occurrence of only one such storm in any particular year tended to increase sharply the annual streamflow as measured at Lee Ferry.

A separate investigation was made to carefully review a 46-year sample in order to find all major storms, to formulate a definition of such storms, and to study the influence on streamflow.

B. PROCEDURE

For purposes of this study of major storms the initial sifting of data was based on the collection of all cases when one-half or more of the several stations in each of three major sub-basins were equal to or above certain low threshold values.

After all such storms had been tabulated, the next step was to establish higher minimum limits for the total quantity of precipitation per storm.

Although the original tabulation was made separating the basin into three sub-basins representing Main Stem, Gunnison, and San Juan, it was eventually determined that only general storms

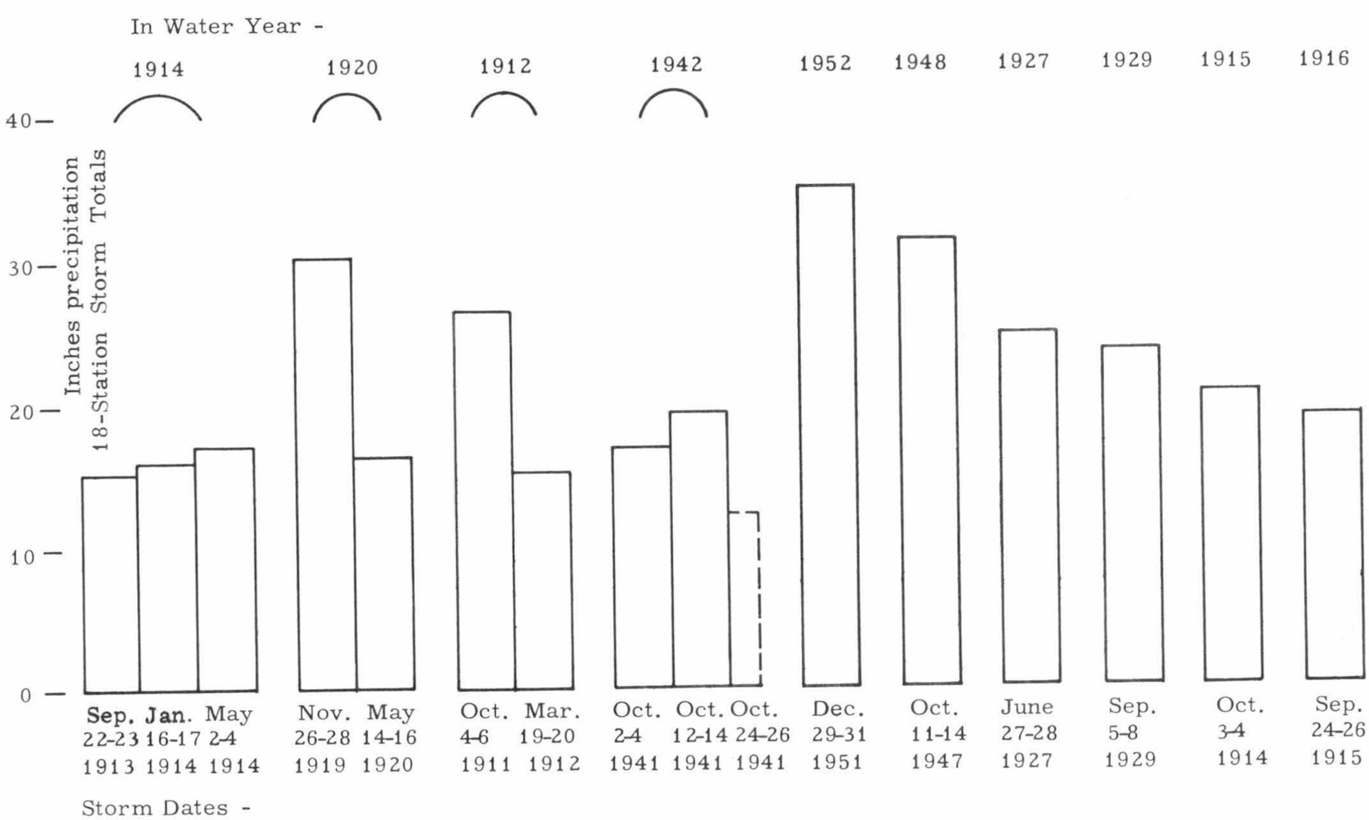


Fig. 33. Listing of the 15 largest major storms occurring in Western Colorado during the 46-year period, 1911-12 - 1956-57. Note that these occurred during only 10 of the 46 water years.

---

* Major storms as treated in this section should be distinguished from the storm periods discussed in other sections.

involving the whole area were large enough to produce a sizeable response in flow measured at Glen Canyon. Streamflow reference material used was the "Present Modified Streamflow of the Colorado River at the Glen Canyon Dam Site." (Unpublished data supplied by Mr. R. Riter of Bureau of Reclamation, Denver).

C. RESULTS

It was found that any major storm which affected the three sub-basins had but less than 15 inches total from the 18 stations tended to have little immediate effect on subsequent streamflow measured at Glen Canyon. Although it is highly desireable that some adjustment be made for the time of year when the storm occurs when deciding on its relative importance to streamflow, for purposes of this particular analysis a fixed value was used for the entire year.

In Figure 33 we find the 15 storms which have occurred in the 46-year period having total precipitation amounts above 15 inches as measured at the 18 stations in Western Colorado.

It was somewhat surprising to find that in four of the seasons more than one such storm occurred. Referring to Figure 33 we note that in the water year of 1913-14 there were three storms separated by two months or more which produced 15 inches in two or three days respectively. While it is true that the storm of September 22-23, 1913, actually produced precipitation prior to October 1, the streamflow response measured at Glen Canyon would have been in the 1914 water year.

A similar situation occurred in late September of 1915 when the storm occurring between the 24th and 26th could not have produced any large increase in runoff measured at Glen Canyon until after October 1. The situation in 1929 was somewhat different in that the storm occurred the early part of September and a goodly portion of the increase in runoff was measured in that same month at Glen Canyon. This was, however, a case in which some of the precipitation in September did influence the following water year and produced abnormally high amounts of runoff for the respective quantity of precipitation measured in 1929-30 water year.

Table V furnishes a very rough approximation of the resulting change in annual streamflow measured at Glen Canyon during water years when the major storms occurred as listed in Figure 33. The simple method of analysis was to determine the percentage relationship of precipitation totals--including the major storms--in each of the various

TABLE V

Rough approximation of response in increased annual streamflow at Glen Canyon related to major storms occurring in Western Colorado. (Stream-flow Unit - 1000 acre-feet).

Water Year Containing 1 or more Major Storms (See Fig. 33)	Percentage of Annual Average Precipitation Recorded Oct. - Sept.	Resulting Runoff when same Percentage is Applied to 46-Season Average Runoff of 12,640	Actual Water Year Runoff Recorded	Extra Runoff which may be due to Major Storms
1914	112	14,157	18,007	+ 3,850
1920	111	14,030	18,818	+ 4,788
1912	114	14,410	17,421	+ 3,011
1942	101	12,766	16,394	+ 3,628
1952	122	15,421	17,613	+ 2,192
1948	104	13,146	13,224	+ 78
1927	139	17,570	15,570	- 1,780*
1929	133	16,811	18,387	+ 1,576
1915	93	11,755	11,605	- 150
1916	115	14,536	16,307	+ 1,771

* Three-basin major storm in June and special 14-day rainy period in September resulted in + 3,104 excess streamflow following year when annual precipitation was 90 per cent. The combined two-season net excess is + 1,324.

seasons as compared with the long-period annual normals for the same set of stations. When this same percentage is applied to the 46-season (1912-1957) average annual streamflow of 12,640,000 acre-feet at Glen Canyon, we can relate this to the actual flow which was measured in that water year to get a rough approximation of the influence of these particular major storms--or multiple major storms.

Table 5 shows the results without considering any influence from other tributaries above Glen Canyon and can, at best, only be considered as a general guide. Several criticisms can be made of this simple technique in determining major storm influence, but it cannot be denied that these major storms do exert a strong plus factor to increasing streamflow.

The total extra runoff for the 15 storms during the ten seasons when they occurred amounted to 22,068,000 acre-feet. This would be an average per major storm of 1,400,000 acre-feet. This is in addition to the direct fractional portion of the total annual runoff attributable to the fractional portion of the annual precipitation produced by each single storm.

D. CONCLUSIONS FROM STUDY OF MAJOR STORMS

Having reviewed the historical record of major storms and, in a very general way, the respective influence these storms have had on run-off, the following conclusions have been reached:

1. A three-basin major storm is defined as one which produces precipitation above 5 per cent of annual precipitation at one-half or more of the stations in each of the three sub-basins and produces an 18-station total precipitation greater than 15 inches. This is to be collected in a period not to exceed four days.

2. Snowpack totals can be used as a general substitute for an annual "major storm." The cumulative total of this "major storm" will differ markedly from year to year, but will have a high correlation with the total annual runoff figures at Glen Canyon.

3. Major storms capable of producing within four days an extra yield of 1,500,000 acre-feet or more of runoff are not a part of the annual recurring weather phenomena. Therefore, long-term planning for the most probable one-year runoff values should permit exclusion of the extra runoff yields obtained from such major storms. A projected five-year sample could logically contain one such storm.

4. Major storms can be identified from the current network of precipitation stations the day following their occurrence.

5. The occurrence of even one major storm adds a plus factor to the impending annual runoff total. However, the one storm, in itself, does not indicate an above normal water runoff year. This will also depend on the precipitation occurring during the other 361 days.

6. Since most major storms occur in the four-month period, September through December, a favorable lead time is gained to allow an upward adjustment of the late winter and early spring runoff estimates for the balance of the current water year.

IV. MOISTURE SOURCES FOR PRECIPITATION IN THE UPPER COLORADO RIVER BASIN

A. OBJECTIVES

The inland location of the catchment area of the Upper Colorado River Basin receives its moisture from air masses which have been modified by travel over a considerable distance of land.

The objective of this special study of moisture source was to determine whether precipitation falling in the Upper Basin has originated from (a) the Pacific Ocean, (b) the Gulf of Mexico, or (c) repeat precipitation from nearby evapotranspiration.

B. PROCEDURE

The method of study has been examination of the weather map sequence related to all storms which occurred in a 46-year period. By moving backward in time from the periods when precipitation has been measured, it is possible to estimate the original source region for the moisture. Only broad generalizations could be made, since any air mass picks up moisture over a long period of time, and it is not possible to fix any small source region. For instance, the air which moves from east to west over the Gulf of Mexico previously has been moving over the Central Atlantic Ocean, and part of the moisture which it contains as it arrives over Mexico may have been picked up through the evaporation process severl thousand miles upwind.

Following preliminary investigation, it was decided that source regions could be better classified into three general categories. These were (1) Gulf of Mexico, (2) Pacific Ocean, with a trajectory south of the high Sierras, and (3) modified Pacific air mass which moved from west to east crossing mountainous terrain at some point north of the south end of the high Sierras.

C. RESULTS

Figure 34 shows the general areas of source regions for precipitation collected in the Upper Basin of the Colorado River.

1. Summer

Summer shower activity occurs mainly in July and August. The source region is primarily the Gulf of Mexico, and some local evapotranspiration brought about by collection of moisture through evapotranspiration within one day's travel time from the south and southwest. The typical trajectory of warm and moist air moves over northern Mexico and then to the north over Utah and Colorado. The high mountainous terrain experiences more showers and has a greater reliability for precipitation during this period than low elevations. The north end of the basin in Wyoming is at a maximum distance from the Gulf of Mexico, and consequently receives a smaller amount of rainfall from summer showers.

2. Fall

During the fall period when general rains can occasionally occur, there is still a general source region from the Gulf of Mexico, but an important alternate source region comes from the warm Pacific south of the high Sierras. Most of the major storms--which have less than an annual frequency of occurrence--come from this source region in the period between September and December. A few of the most notable storms of this period have actually been remnants of a storm which was a hurricane of tropical origin in the Pacific Ocean south and west of Mexico. The movement of such a storm carries tremendous quantities of moisture as it moves from near the mouth of the Colorado River up to the upper catchment basin. Such storms are particularly important in producing precipitation in the south half of Utah and the southern slopes of the mountains in Colorado.

3. Winter

Nearly all of the wintertime precipitation comes from air masses which have moved from west to east across the mountainous terrain, extending from the south end of the high Sierras to the Canadian Border. The actual trajectory of some of this air moves eastward into Montana and then southward into the Upper Colorado River Catchment Basin. Such trajectory produces the greatest amount of precipitation on the northern and northwestern slopes of mountainous terrain.

Precipitation activity is accentuated greatly at the higher elevations, since a large amount of lifting and cooling is required to produce precipitation from this air after its passage over the mountainous terrain upwind. An extreme example of such an influence of the upwind mountains can be illustrated from a trajectory moving toward Colorado across the high Sierras of California. Such an air mass would lose a very high fraction of its moisture as it moved upward over the mountain barrier in California. As this air mass moves downslope on the east side of the Sierras, it is heated and can continue to carry all available moisture in vapor form until it is again lifted and cooled moving against the very high terrain in the Rocky

Mountains. Thus, at lower elevations, little or no precipitation is received during the winter months, while at the very high elevations cloudiness and light snow are very frequent. In a few rare instances, the large cyclonic storm can move into North America in the period between December and March to the south of the high Sierras. Such storms can carry large amounts of moisture toward the northeast through the relatively low terrain across the desert. This moisture is then subsequently precipitated into the upper basin areas in large amounts.

At the end of the winter period, primarily in April and May, there is a storm tendency for cyclonic storms to be generated over the State of Arizona, and their movement is relatively slow during the formative stage. These storms pull in air which has originally moved over New Mexico from the Gulf of Mexico. As these storms move to the northeast across the state of Colorado, heavy moisture deposits are delivered to the eastern slopes, and some precipitation is moved into the northern portion of the upper basin area from a trajectory moving around the cyclone and into the basin from the northeast. It is quite unfortunate that this precipitation process is limited to less than 36 hours, since the cyclonic storm is moving toward the northeast at a rather rapid rate.

D. CONCLUSIONS FROM STUDY OF MOISTURE SOURCES

1. Moisture from the Pacific in the wintertime is reliable in producing some snowpack in higher elevations every year.

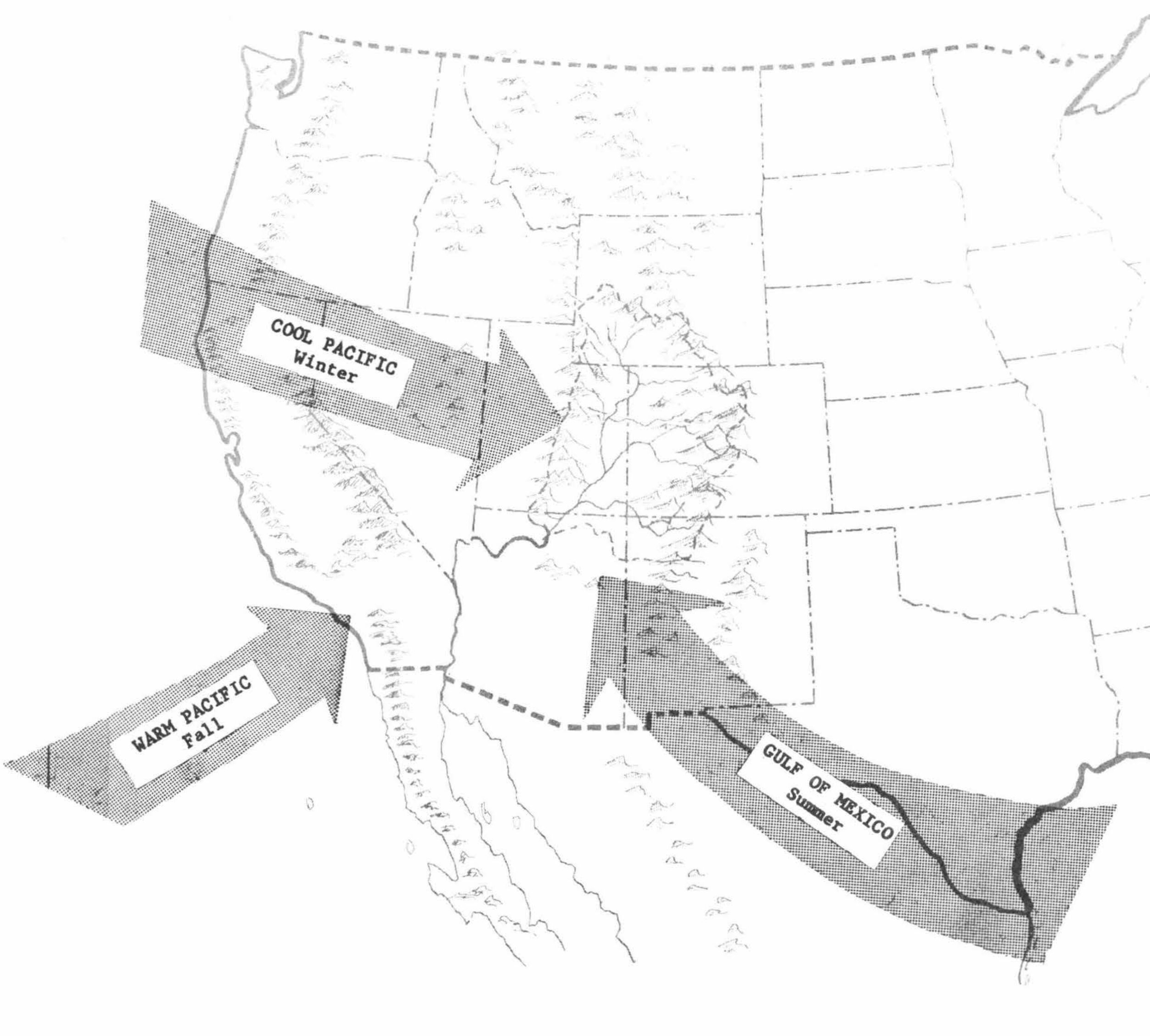


Fig. 34. Source Regions for precipitation in the Upper Colorado River Basin.

2. Summer thunderstorms drawing moisture from the Gulf of Mexico are most reliable in the high mountainous terrain and the south edge of the catchment basin.

3. Fall storms from the source region of the warm Pacific are not reliable on an annual basis, but when they do occur, can generate major quantities of precipitation.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

A large mass of data have been prepared in readily available form for computer analyses. These data have been by no means exhaustively treated in this study.

The availability of these "refined" climatological data makes it possible to use the probabilistic approach for short term (less than one year) forecasts of precipitation events.

In nearly all of the precipitation data included in this report, the mean or average values are higher than the median values. This positive skewness is typical of precipitation data, particularly in semi-arid areas.

This difference between the mean and median values means that in most cases the amounts of precipitation that will be received 50 per cent of the time will be less than the average amounts. Therefore, the average amounts are somewhat misleading because they will not be received 50 per cent of the time.

Major storms are significant contributors to runoff from the Upper Colorado River Basin. These major storms can be identified from existing precipitation stations shortly after they occur.

The primary moisture sources of precipitation in the Upper Colorado River Basin have been identified as being from the northern Pacific in the winter, southern Pacific in the fall, and from the Gulf of Mexico in the summertime.

B. RECOMMENDATIONS

Further research should be accomplished to explore different levels of "drop outs" as a means of adjusting observed precipitation data to give observed runoff. Studies such as the one described in this report for the Gunnison River would be of value, not only for the development of prediction equations for seasonal runoff, but also as a means for obtaining a better understanding of the physical processes involved in the rainfall-runoff relationship.

It is desirable to have additional observing stations for precipitation at elevations higher than 6000 feet msl. Because of the high evapotranspiration amounts for elevations below 6000 feet msl in the Upper Colorado River Basin, additional stations below 6000 feet would be of questionable value.

In view of the importance of major storms, particularly in the fall, it would be desirable to conduct "bucket surveys" for major storms occurring in the fall of the year. Such "bucket surveys" would give a better measure of the total quantity of precipitation that falls. This information should be valuable in making estimates of runoff to be expected during the following spring season.

It is recommended that short-term planning make use of the data that can be obtained from the occurrence of major storms as they happen. For example, if a major storm occurs in the fall of the year, it is quite likely that additional runoff can be expected the following spring. Conversely, if no major storm occurs in the fall of the year, it is likely that the amount of runoff to be expected the following spring will be relatively low. This concept should be of value in planning for the runoff.

Any future plans for attempting to increase precipitation by artifical means must necessarily consider the moisture source, and any operational plans must be based on the primary sources of precipitation available. This means, for example, that attempts at increasing precipitation in the wintertime should exploit the availability of moisture from the Pacific northwest. Conversely, any attempt at weather modification that would plan to use moisture from the same region in the summertime would likely be foredoomed to failure. Any plan which would not recognize the differences between moisture sources in any season would not represent proper planning.

It is recommended that the present study be considered only a beginning of a better understanding of the precipitation occurrences in the Upper Colorado River Basin. Future work on this subject will be of considerable value in gaining a better understanding of the hydrologic process that effect the economy of the Upper Colorado River Basin.

VI. APPENDICES

A. PROCEDURES FOR MACHINE PROCESSING OF PRECIPITATION DATA

Step 1. Punching of Daily Cards

Data as taken from the stations involved in this project, were punched into cards using the following format:

Columns	
1, 2	state
3-6	alpha order no.
7, 8	year
9, 10	month
11, 12	day
13	division
14-16	max. temp. (degrees F)
17-19	min. temp. (degrees F)
23-26	precip. (hundreths of an inch)
27-29	24 hr. snow fall (tenths of an inch)
30-32	snow depth (inches)

11 punches were used in the following columns:

14, 17	negative temperature
30	no snow on ground
26, 29, 32	trace of precip. or snow
25, 28	precip. or snow recorded next day
23, 27	no precip. or snow

Blanks were in columns 23-26, 27-29, 30-32 if no observation (a day with no record) was reported.

Step 2. Listing of Daily Cards

A list by months was prepared on the IBM 402. Monthly totals for all items in step 1 were computed, and the presence of 11 punches and blanks was indicated.

Step 3. Errors in Daily Cards

The list acquired in step 2 was used to check for errors in punching. The totals were compared with totals available from the U. S. Weather Bureau. Also the totals for the first 6 items (cols. 1-13) in step 1, were checked to insure correct identification and date. Discrepancies were corrected by checking each day in that month.

Step 4. Corrected Daily Cards

Daily cards found to be in error in step 3 were repunched and verified. These corrected daily cards replaced the daily cards that were in error. This procedure was done by hand due to the possibility of date errors and the small number of corrected cards as compared to the original cards.

Step 5. Duplication of Daily Cards

All daily cards, as corrected, were duplicated on the IBM 514. One set was sent to the U.S. Weather Bureau and the other set was retained for further reduction and analysis.

Step 6. Storm Summarization

In reducing the daily cards to a smaller, more workable set of "summary cards" the following definitions were used: A storm consists of consecutive days with precipitation greater than trace. A storm period begins with the first day of precipitation in a storm and ends with the day preceding the following run of consecutive days with precipitation, as shown in the example below.

Only the station identification, data and precipitation (columns 23-26 on the daily cards) were used in this operation.

Daily Cards																	
Daily Cards	Precip.	0	0	.2	.4	0	0	.2	T	.6	.8	0	T	T	0	0	.5
	Serial date	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Summary Cards	Storm 1 (days 3-6)	Storm 2 (days 7-8)	Storm 3 (days 9-15)
Storm Serial No.	1	2	3
Precip.	0.6	0.2	1.4
Serial day storm ends	6	8	15

Boards were wired for the IBM 402 and IBM 514 for a summary punching operation to obtain the following information on the new deck of "storm" summary cards:

a) precipitation per storm
b) accumulated precipitation
c) storm serial number
d) serial day storm ends
e) number of days with precipitation this period
f) accumulative days with precipitation
g) days with trace this period
h) accumulative days with trace
i) days with no precipitation this period
j) accumulative days with no precipitation
k) days with no record
l) accumulative days with no record
m) serial year (October 1, 1800 begins serial year 000)
n) 11 punch to indicate 1st storm in each serial year

The boards for this step were quite involved and required several hours of experimentation with timing, selectors, emitters, etc. Due to the time involved in wiring these boards, the wiring diagrams will be made available upon request to the author.

Step 7. Summary Card Check of Storm Cards

Simultaneously with the summary punching of storm cards, a list was made. The following visual checks were made to insure proper punching:

a. check precipitation per storm to check for excessive amounts
b. scan months for order in each serial year
c. check for a change of only one year within each serial year
d. check serial year order

If any of these checks indicated improper sequencing or other errors, that portion was rerun Part (c) could be in error if a year was missing or if the month of October was missing, as a serial year begins with October 1. In case of this type of error, partial serial years were rerun.

Step 8. Serial Day Storm Begins

In the analysis of the storms it was necessary to have the serial day that each storm began. On the IBM 514 the last day of the previous storm was punched into each card, except for the first storm in each serial year. One day was added to this figure to obtain the serial date for the beginning of each storm.

Step 9. Last Storm in Serial Year

In step 10 (see below) an 11 punch was used to identify the last card in each serial year. To accomplish this, in step 9 the cards were run in reverse order on the IBM 514 and the 11 punch identifying the first card in each serial year was punched into a different column of the next card. This card then was the last card of the previous serial year, due to the reverse order.

Layout for Storm Summary Cards

Columns	
1,2	state
3-6	alpha order number
7,8	year
9,10	month
11,12	day
13	division
14-18	precipitation this storm
19-23	accum. precipitation
24-26	storm serial number
27-29	serial day storm starts
30-32	days with precipitation this period
33-35	accum. days with precipitation
36-38	days with trace this period
39-41	accum. days with trace
42-44	days with no precipitation this period
45-47	accum. days with no precipitation
48-50	days with no record this period
51-53	accum. days with no record
54-56	serial year
57-75	blank
76	11 punch last card in year
77-79	serial day storm period ends
80	11 punch 1st card in year

Step 10. Last Card List

A list was made consisting of the last card for each serial year. Because a deck of last cards was desired for step 11 this operation was performed as summary punching. The board for the IBM 402 was wired to list the last card and summary punch a duplicate of it by a minor program, which was started by a change in serial year. The counters, however, were pulsed to add by the 11 punch in last cards. A check of the list then gave another check for correctness in the summary cards. A check on the "serial day storm ends" column told how many daily cards there were in each year. Years having fewer than 360 daily cards were not included in the analysis.

Step 11. Analysis of Missing Precipitation Data

The last cards obtained in step 10 were used to make a frequency of the number of days with no record of precipitation for each water year. It was decided to eliminate all years having more than 35 days of missing precipitation data.

Step 12. Unusable Years

The partial years of less than 360 days, and/or the years with more than 35 days of missing precipitation data, were removed from the deck of summary cards.

Step 13. Transfer to Tape

The analysis on the 1620 required all input to be on 8 channel paper tape. The following information was transferred from each summary card: month, storm precipitation, serial day storm starts, number of days with no record, serial year and a record mark (end of line). In addition, at the end of the last card in each serial year, an extra record mark was punched.

Step 14. Summary Card Analysis

A program was then written for the IBM 1620 to obtain the following information:

Figure

2 annual precipitation mean and variance
3 number of storms mean and variance
4 annual precipitation mean and variance for storms with precipitation greater than zero after subtracting assumed evapotranspiration losses, depending on the altitude of the station and the month the storm is in.
5 number of storms mean and variance after evapotranspiration reductions
6 percentage mean and variance of the number of storms comprising 25 per cent of the annual precipit ation
7 same as 6, for 50 per cent of annual precipitation
8 same as 6, for 75 per cent of annual precipitation
9 serial day mean and variance that 5 inches of accumulative precipitation was received. Also the fraction of years of record in which 5 inches was received
10 same as 9, for 10 inches
11 same as 9, for 15 inches
12 same as 9, for 20 inches
13 same as 9, for 25 inches
14 probability of receiving 5 inches of precipitation after 1 January, 1 March and 1 May
15 same as 14, for 10 inches
16 same as 14, for 15 inches
17 same as 14, for 20 inches
18 October precipitation mean and variance
19 November precipitation mean and variance
20 December precipitation mean and variance
21 through 29 January through September precipitation mean and variance
30 extremes and 25, 50, and 75 percentiles for figures 2 through 13 and 18 through 29
31 an ordered list, by years, of the precipitation in January, July, and then the entire year. From this a frequency distribution was made.

Note: The program as written used the numbering as listed above. In preparation of the final copy of this report, the numbering system was changed so that Figure 2 became 3, Figure 3 became 4, etc.

The values for figures 2, 3, 4, and 5 were corrected for days with no record. At the end of each year, these values were multiplied by $\frac{365}{365-A}$ where A is the number of days with no record.

Upon request, the program for step 14, either in list or cards for the source program, or tape for the object (machine language) program, will be made available.

B. CATALOGUE OF DATA AVAILABLE AT COLORADO STATE UNIVERSITY

1. Daily climatological data cards as specified in Appendix A, step 1, and as listed in Table I and Figure 1 in this report.

2. A listing of corrected daily cards, for the same stations and periods as noted in paragraph 1 above.

3. Summary cards for storm totals as described in steps 6, 7, 8, and 9 of Appendix A.

4. Storm card listings for the storm cards as described in paragraph 3 above.

5. Cards for the last storm in a serial year as described in step 9 of Appendix A.

6. A listing of the data from the last storm in the serial year as described in step 9 of Appendix A.

7. Various (hand) compilations of basic data have been made during this study. These compilations can be made available on request.