ANALYSIS OF COLORADO PRECIPITATION

by

Marie Kuo and Stephen K. Cox

June 1975

ENVIRONMENTAL RESOURCES
CENTER

Colorado State University
Fort Collins, Colorado

Completion Report Series
No. 63

ANALYSIS OF COLORADO PRECIPITATION

Completion Report

OWRR Project No. A-018-COLO

by

Marie Kuo and Stephen K. Cox

Department of Atmospheric Science

Colorado State University

submitted to

Office of Water Resources Research
U.S. Department of the Interior
Washington, D. C. 20240

June 1975

The work upon which this report is based was supported (in part) by funds provided by the United States Department of the Interior, Office of Water Resources Research, as authorized by the Water Resources Research Act of 1964, and pursuant to Grant Agreement No. 14-31-0001-A-018-COLO.

Colorado Water Resources Research Institute
Colorado State University
Fort Collins, Colorado 80523

Norman A. Evans, Director

TABLE OF CONTENTS

Completion Report

ABSTRACT

'ANALYSIS OF COLORADO PRECIPITATION'

The objectives of the research proposal 'Anlaysis of Colorado Precipitation' fall into two categories. Firstly, 56 years of precipitation history were used to determine if there are any significant trends in regional and statewide precipitation in Colorado. This portion of the research is complementary to the work of Sellers (1960) who used the 90 year running mean of annual precipitation for 18 stations of Arizona and western New Mexico.

Secondly, 20 years of Colorado hourly precipitation data were used to represent precipitation events, called 'storms', and the data were examined to find storm frequency, length and yield. The storms were divided into size categories and were used to determine the contribution of each size of precipitation event to the annual total. Data from the western part of the state has been studied extensively because it is part of the upper Colorado River Basin which supplies water to the arid southwestern United States. Marlatt and Riehl (1963) found that most of the precipitation is produced in a few days and the amount of precipitation is correlated with the fraction of area receiving precipitation. In a comparison paper by Riehl and Elsberry (1964), consecutive days with precipitation were grouped together to form storms. The precipitation derived from medium size storms of 0.3 to 1.2 inches were found to be most closely related to the annual precipitation in the basin, and the size of storms roughly corresponds to the duration of the episode.

1. ANALYSIS OF PRECIPITATION TREND

Colorado has an area of 104,247 square miles with approximately 300 weather stations distributed throughout the state. Sixty-one of these Colorado stations have precipitation records of fifty years or longer.

1.1 Trend Analysis

The 61 long-term stations used in this analysis are listed alphabetically in Table 1. The locations of the stations are shown in Figure 1.

A straight line was fitted through a time series of annual precipitation data from each station to detect any increasing or decreasing precipitation trend (Draper and Smith, 1966). The slope and correlation coefficient were calculated for each of the long-term stations. The results are shown in Table 1. The average slope of all the stations is -0.009 inches per year i.e., an average decrease of one inch every 120 years.

To see if the apparent decrease in precipitation is due to the natural variability of the annual precipitation or to a change in climatic regime, a correlation coefficient between the annual precipitation and time was calculated. The results are shown in Table 2.

A histogram of the correlation coefficient is plotted in Figure 2. The distribution is normal with an average correlation of 0.07 and 47 percent of the stations have correlations in the interval between -0.15 and 0.0. If this average correlation coefficient is assumed to be constant and none of the other parameters change, it would take approximately 800 years of data for a correlation of 0.07 to be significant at the 5 percent level. Such an extrapolation is not valid since annual precipitation is

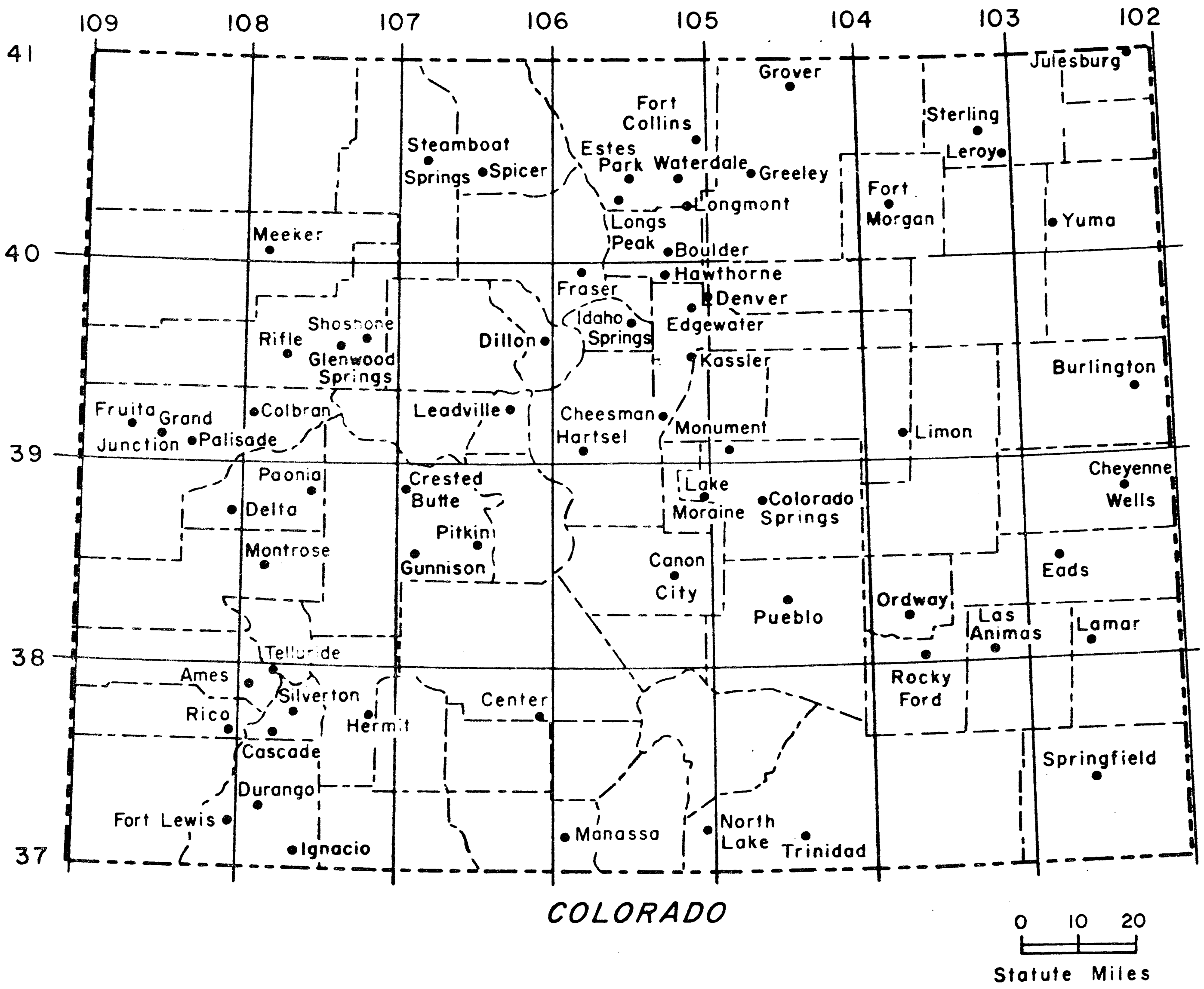

Figure 1. Location of stations whose precipitation records were used in the trend analysis.

TABLE 1

SUMMARY OF LONG-TERM STATIONS AND THEIR TRENDS

NAME	LENGTH OF RECORD	DATE OF RECORD	SLOPE in./yr.	CORRELATION COEFFICIENT	SIGNIFICANT LEVEL 5%	10%
Ames	57	1914-1970	.028	.09		
Boulder	78	1893-1970	.016	.08		
Burlington	80	1891-1970	-.025	-.12		
Canon City	74	1897-1970	.001	.01		
Cascade	51	1907-1959	-.114	-.20		
Cheesman	68	1903-1970	-.007	-.04		
Cheyenne Wells	74	1897-1970	-.029	-.13		
Collbran	75	1892-1966	-.034	-.21		X
Colorado Springs	79	1892-1970	.081	.10		
Crested Butte	61	1910-1970	.054	.14		
Delta	83	1888-1970	-.006	-.07		
Denver City	99	1872-1970	-.016	-.12		
Dillon	58	1913-1970	-.048	-.23		X
Durango	76	1895-1970	-.013	-.05		
Eads	54	1917-1970	.011	.04		
Edgewater	53	1909-1961	-.033	-.12		
Estes Park	61	1910-1970	-.092	-.33	X	X
Fort Collins	84	1887-1970	-.000	-.00		
Fort Lewis	59	1912-1970	-.009	-.03		
Fort Morgan	82	1889-1970	-.023	-.16		
Fraser	61	1910-1970	-.008	-.04		
Fruita	63	1908-1970	-.050	-.33	X	X
Glenwood Springs	61	1910-1970	.008	.04		
Grand Junction	79	1892-1970	-.002	-.02		
Greeley	79	1888-1966	-.015	-.10		
Grover	58	1912-1969	-.016	-.07		
Gunnison	70	1901-1970	.023	.19		
Hartsel	57	1909-1965	-.011	-.06		
Hawthorne	61	1910-1970	-.026	-.10		

TABLE 1 - Continued

NAME	LENGTH OF RECORD	DATE OF RECORD	SLOPE in./yr.	CORRELATION COEFFICIENT	SIGNIFICANT LEVEL 5%	10%
Hermit	61	1910-1970	-.065	-.27	X	X
Idaho Springs	66	1905-1970	.005	.03		
Ignacio	57	1914-1970	-.072	-.29	X	X
Julesburg	59	1912-1970	-.024	-.09		
Kassler	72	1899-1970	.019	.09		
Lake Moraine	69	1895-1963	-.031	-.12		
Lamar	82	1889-1970	-.014	-.08		
Las Animas	104	1867-1970	.011	.09		
Leadville	63	1908-1970	-.055	-.23		X
Leroy	82	1889-1970	.031	.18		
Limon	63	1908-1970	.014	.06		
Longmont	60	1911-1970	-.041	-.18		
Longs Peak	53	1895-1943	.070	.21		
Montrose	71	1900-1970	.003	.02		
Monument	53	1911-1963	-.011	-.04		
Ordway	50	1921-1970	-.003	-.01		
Palisade	59	1912-1970	-.031	-.20		
Paonia	71	1900-1970	-.013	-.08		
Pitkin	61	1910-1970	.043	.20		
Pueblo	84	1887-1970	-.007	-.05		
Rico	61	1910-1970	.030	.09		
Rifle	59	1912-1970	-.012	-.07		
Rocky Ford	82	1889-1970	-.017	-.11		
Shoeshone	61	1910-1970	.085	.40	X	X
Silverton	64	1907-1970	-.095	-.31	X	X
Spicer	61	1910-1970	.067	.45	X	X
Springfield	56	1915-1970	-.039	-.14		
Steamboat Springs	62	1909-1970	-.016	-.07		
Sterling	61	1910-1970	-.007	-.04		
Telluride	59	1912-1970	.011	.03		
Waterdale	76	1895-1970	-.008	-.04		
Yuma	80	1890-1970	.010	.05		

TABLE 2

SLOPE AND CORRELATION COEFFICIENT OF AVERAGE ANNUAL PRECIPITATION

		β SLOPE IN INCHES/YEAR	r CORRELATION COEFFICIENT	NUMBER OF YEARS OF DATA	DATE
19	Stations with no estimated values	-.021	-.14	58	1913-1970
29	Stations with estimated values	-.016	-.10	56	1914-1969
21	Eastern slope stations	-.016	-.08	55	1915-1969
14	Western slope stations	-.011	-.06	57	1914-1970
7	Oil shale stations	-.025	-.17	55	1912-1966
	Whole state weighted by area contributed by 43 stations	-.009	-.06	56	1910-1965

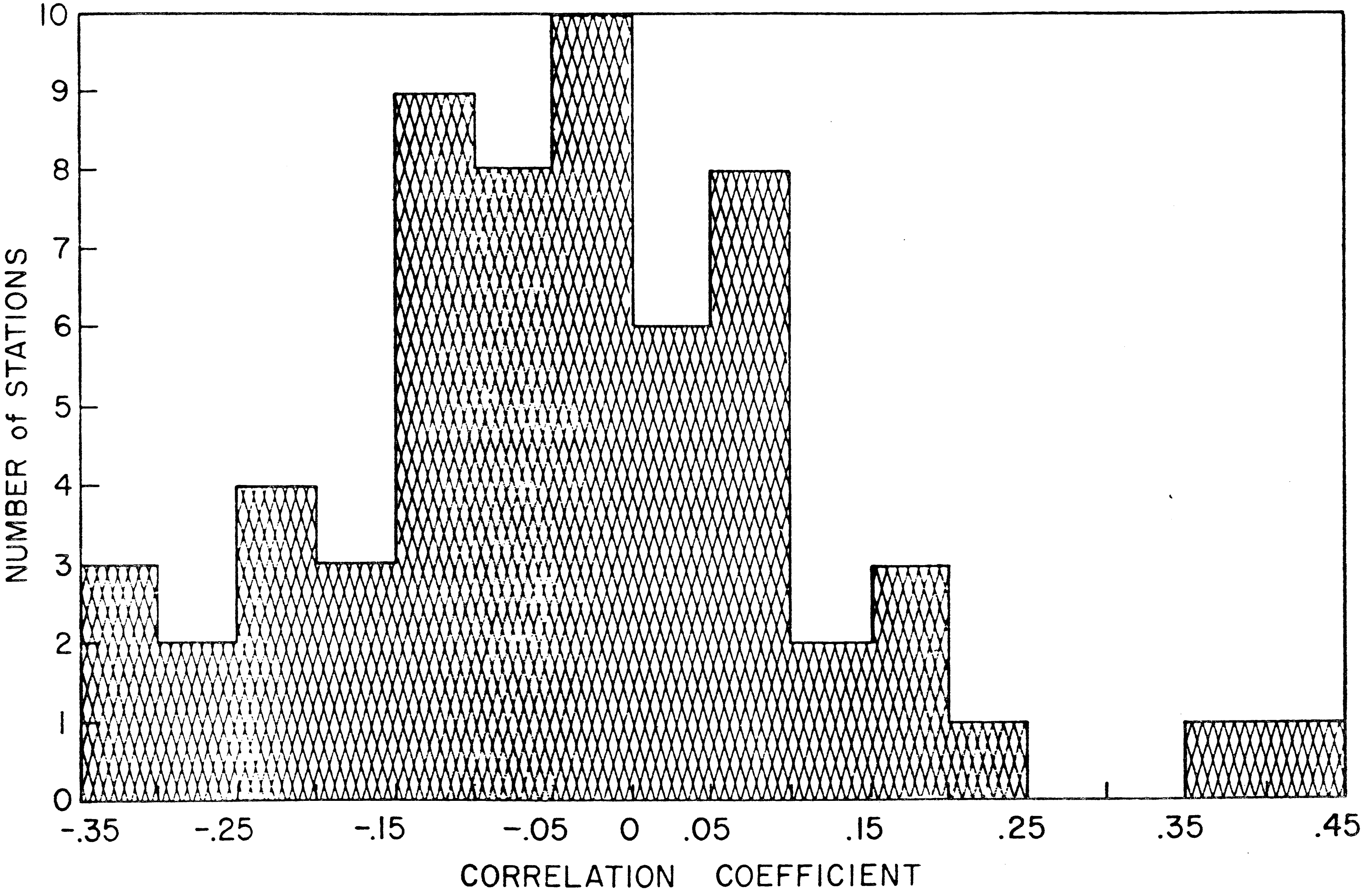

Figure 2. Histogram of Correlation Coefficient

not constant, thus, both the slope and correlation are not constant. If any real trend exists, the correlation coefficient would become significant in a much shorter time period.

The annual area weighted precipitation of Colorado from 1910-1965 is shown in Figure 3. There are extended periods of relatively dry and wet years. The overall picture, however, does not show any noticeable increase or decrease of precipitation.

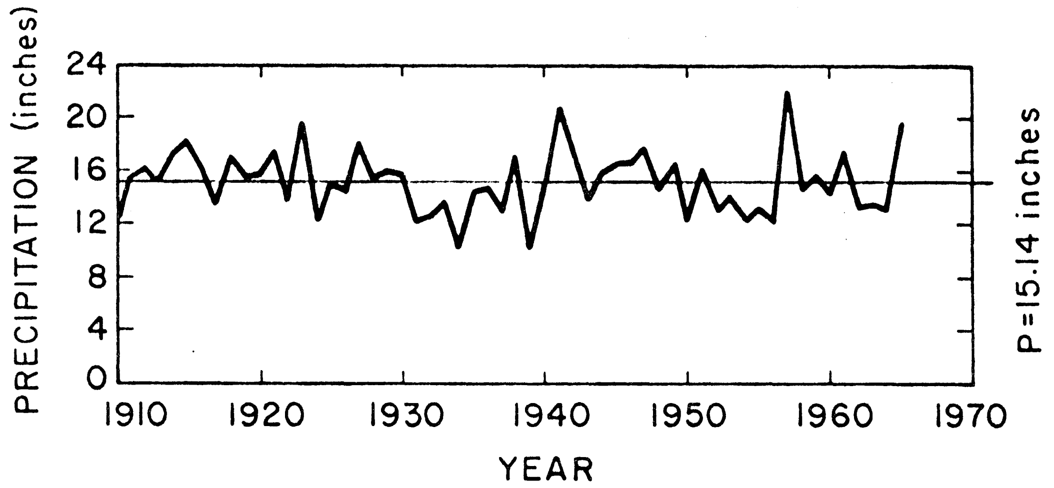

Figure 3. Area weighted precipitation of Colorado 1910-1965.

In conclusion, there was found no statistically significant trend in the statewide precipitation even though several individual stations do show long term trends.

2. CORRELATION BETWEEN STATIONS

It would be useful to find out if the precipitation measurements from a few stations are representative of the area concerned. Since precipitation in an area is always approximated by measurement at a location, a test of how well the data at a station approximates data from other stations in the same vicinity may give an indication of how well a station may represent an area.

Climatically, precipitation in Colorado is deposited by different mechanisms associated with the two seasons separated by transition periods. In the winter, the precipitation is usually generated by storms of cyclonic scale of 500 to 1000 miles. Precipitation accompanying the storm generally occurs over a large area so that any analysis of correlation of precipitation between adjacent stations should yield high correlation coefficients. In the summer, the weather is brought about by small disturbances in the upper atmosphere of the same scale as the winter, but they are much weaker and do not have precipitating storm systems associated with them. Instead, the waves set up atmospheric conditions conducive to convective activity producing thunderstorms over the entire region. These thunderstorms have diameters of 10 to 20 miles accounting for most of the summer precipitation. Since the activity occurs over a large area producing numerous thunderstorms in the region, correlation should exist, but because of the small precipitating area, the correlation may not be as high as in the winter.

To see how well the precipitation between adjacent stations agree, a correlation coefficient was calculated. The twenty-one long-term stations and their three surrounding stations used are listed in Table 3. Correlation coefficients were computed between the precipitation of the long-term station with the average precipitation of three stations around it for twenty years. The monthly and annual correlation coefficients for each station are shown in Table 4. Referring to the monthly values, the poorest correlation occurs in July and August, and in October 50 percent of the stations have their best correlation. To compare the correlations obtained for the winter months (October - March) with those for the summer months (April - September), a mean correlation coefficient was calculated by averaging the correlations for all stations for the appropriate season. The average summer correlation is 0.78 compared to 0.85 in the winter. So, as expected, the precipitation of adjacent stations correlates better in the winter than in the summer but the difference between them is small. Even though a large part of the summer precipitation is deposited by small scale thunderstorms, the correlation is still statistically significant at the 5 percent level. The annual precipitation is highly correlated between the stations and their surrounding stations. The coefficient is statistically significant at the 1 percent level for each station. This suggests that on a year to year basis, a station may represent its surrounding area and that correlation exists. This result is as expected and is presented to support the contention that a station is representative of an area over a year in spite of the summer convective precipitation events.

3. STORM INFORMATION

In this section, values of hourly precipitation are manipulated to form natural precipitation periods. The hourly precipitation data supply statistics which describe precipitation variation in time: the mean annual rainfall and monthly distribution. These hourly precipitation data, however,

TABLE 3

LIST OF STATIONS USED AND THEIR SURROUNDING STATIONS

NAME	SURROUNDING STATIONS
Boulder	Denver, Longmont, Allenspark
Canon City	Westcliff, Penrose, Pueblo
Delta	Montrose, Cedaredge, Palisade
Denver	Denver AP, Boulder, Castle Rock
Durango	Mesa Verde, Silverton, Wagon Wheel Gap
Fort Collins	Greeley, Longmont, Nunn
Glenwood springs	Shoeshone, Eagle, Rifle
Grand Junction	Fruita, Palisade, Rifle
Gunnison	Crested Butte, Wilcox Ranch, Cochetopa Creek
Las Animas	Lamar, Eads, Ordway
Leroy	Sterling, Akron FAA, Yuma
Longmont	Greeley, Boulder, Allenspark
Montrose	Paonia, Delta, Norwood
Pitkin	Buena Vista, Gunnison, Crested Butte
Pueblo	Fountain, Penrose, Ordway
Rocky Ford	Pueblo, Ordway, Las Animas
Silverton	Telluride, Durango, Wagon Wheel Gap
Springfield	Granada, Kim, John Martin Dam
Steamboat Springs	Spicer, Hayden, Yampa
Telluride	Ouray, Silverton, Pleasant View
Yuma	Leroy, Akron FAA, Wray

TABLE 4

MONTHLY, SEASONAL AND ANNUAL CORRELATION COEFFICIENT OF PRECIPITATION OF THE LONG-TERM STATIONS WITH THE AVERAGE PRECIPITATION OF THREE SURROUNDING STATIONS.

NAME	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.	S.	W.	ANNUAL
Boulder	.73	.78	.80	.96	.94	.84	.70	.57	.93	.98	.64	.87	.82	.80	.92
Canon City	.90	.80	.87	.94	.95	.73	.72	.73	.87	.95	.91	.74	.82	.86	.89
Delta	.93	.84	.92	.83	.89	.95	.71	.82	.94	.93	.84	.77	.86	.87	.93
Denver	.92	.87	.86	.95	.94	.81	.90	.69	.93	.97	.73	.90	.87	.88	.93
Durango	.95	.92	.89	.86	.87	.72	.67	.55	.93	.87	.65	.94	.78	.87	.90
Fort Collins	.84	.85	.95	.91	.89	.84	.62	.71	.94	.98	.85	.78	.82	.87	.89
Glenwood Springs	.76	.82	.88	.84	.86	.89	.84	.66	.93	.97	.46	.87	.84	.79	.87
Grand Junction	.87	.83	.94	.81	.87	.85	.78	.87	.93	.94	.80	.94	.85	.89	.93
Gunnison	.93	.85	.81	.44	.86	.83	.76	.54	.78	.91	.85	.62	.70	.83	.76
Las Animas	.94	.97	.94	.96	.79	.84	.61	.46	.75	.92	.84	.92	.73	.92	.77
Leroy	.91	.83	.91	.94	.94	.84	.47	.67	.85	.96	.93	.85	.79	.90	.75
Longmont	.77	.65	.91	.92	.91	.80	.58	.42	.91	.94	.78	.69	.76	.79	.88
Montrose	.57	.63	.85	.78	.91	.83	.78	.62	.95	.87	.71	.43	.81	.68	.87
Pitkin	.88	.81	.86	.59	.90	.90	.70	.69	.95	.90	.76	.86	.79	.84	.66
Pueblo	.94	.68	.54	.87	.77	.68	.42	.35	.84	.60	.92	.93	.65	.77	67
Rocky Ford	.92	.91	.90	.91	.83	.85	.39	.54	.61	.97	.95	.91	.69	.93	.73
Silverton	.83	.94	.90	.73	.88	.90	.73	.71	.94	.92	.87	.94	.81	.90	.88
Springfield	.90	.82	.64	.76	.93	.83	.56	.08	.69	.83	.87	.82	.64	.81	.79
Steamboat Springs	.84	.79	.87	.81	.86	.90	.79	.42	.96	.97	.83	.97	.79	.88	.90
Telluride	.83	.94	.86	.84	.81	.87	.68	.72	.88	.95	.89	.86	.80	.89	.83
Yuma	.89	.83	.80	.94	.74	.91	.49	.76	.91	.95	.93	.72	.79	.85	.73
												AVERAGE	.78	.85	.84

The summer and winter coefficients are averaged over the correlation for April-Sept. and Oct.-March, respectively.

do not include information such as the number of storm occurrences in a year, their duration and the water yielded by each storm. The storm events were computed to give a better picture of how storm passage contributes to the water yield, and to see how precipitation varies in space, time and amount.

3.1 Data Source

Storm data were assembled from hourly precipitation data records over a twenty year period (1951-1970). From 1951 to 1967, precipitation was recorded to one hundredth of an inch. Beginning in 1968, many stations began using the Fisher-Porter gauge. This rain gauge punches a mark on paper tape whenever one tenth of an inch of precipitation is recorded. Thus, the resulting data is not the exact hourly precipitation, but rather, indicates the amount of precipitation between the two time periods when precipitation had been recorded. Precipitation in increments less than 0.1 inches occurring during one day may not have been recorded until many hours later, and therefore, may have been included in another storm.

3.2 Division of Colorado Into Six Regions

Colorado is a mountainous state whose elevation varies 10,000 feet within its boundaries. This wide range in elevation causes large variations in the local climate and especially in orographic precipitation. It would be useful to group stations in the same geographic area together into a region so that the precipitation regime within the area would be more homogeneous. The topography of Colorado and its regional divisions are shown in Figure 4. The Continental Divide runs in a north-south direction, approximately through the middle of the state. To the east, the land flattens to the high plains which makes up about 40 percent of

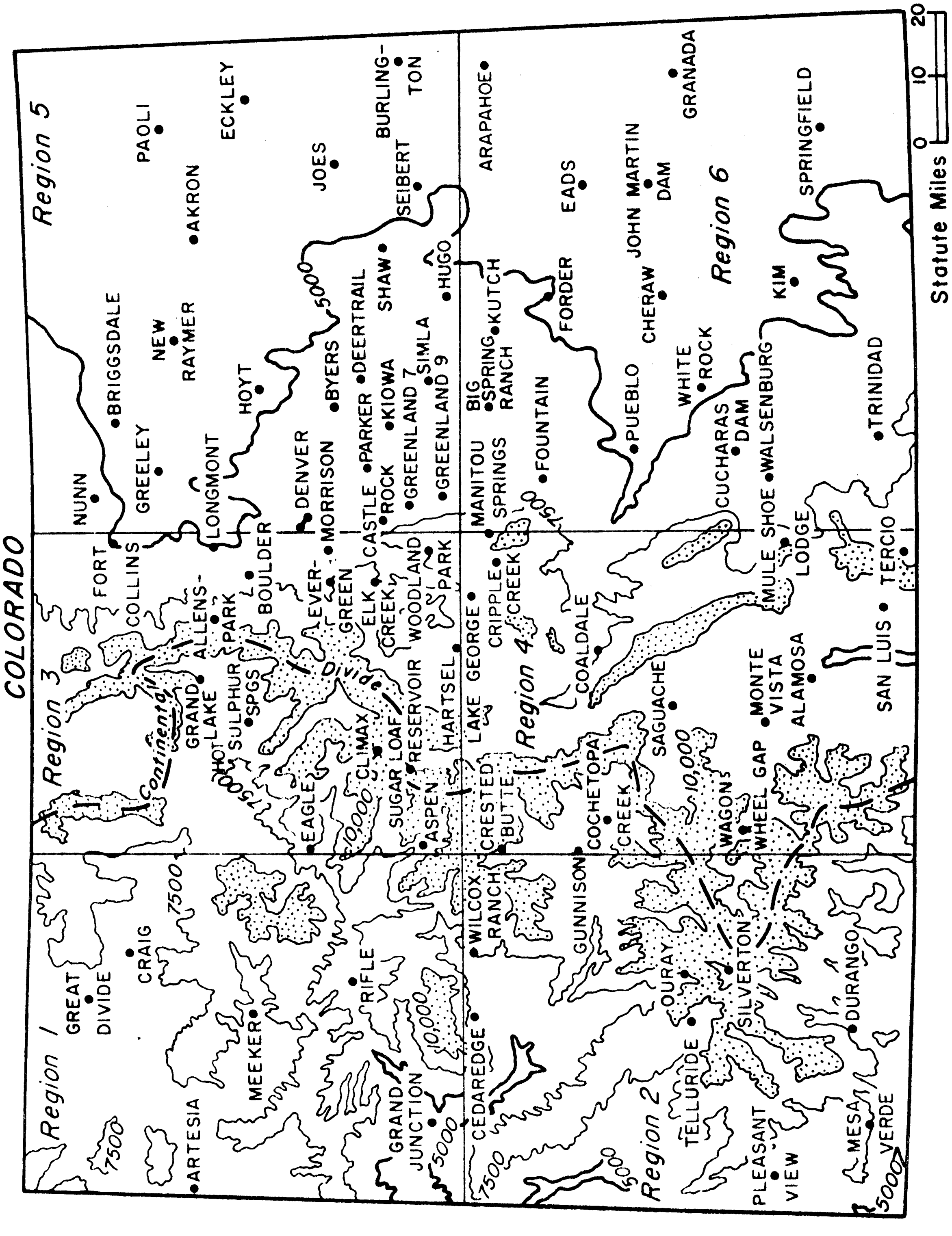

Figure 4. Topographic map of Colorado and the locations of regions and stations whose precipitation records were used in the storm analysis.

the area of the state. To the west, the elevation decreases slightly and there are smaller mountain ranges extending in various directions. The state was divided into six regions to differentiate climatic differences due to topography. The number of stations in each region varies a great deal. The precipitation stations tend to be situated in population centers and are generally found near rivers or are located at the bottom of a valley. Also shown in Figure 4 are the locations of the precipitation stations.

The stations in each region with their areas and elevations are listed in Table 5. The stations used have the longest, most consistent hourly precipitation records. Although a few stations have had names changed or have been moved up to several miles, their precipitation data were used without any adjustment.

3.2.1 Precipitation Characteristics in the Six Regions of Colorado

To illustrate how the precipitation of one region differs from another as an indication of the validity of the regional divisions, the average monthly precipitation of each region is shown in Figure 5. These average values were taken from the Monthly Normal Precipitation 1941-1970, and subdivided into the same six regions. Region 1 is the oil shale area which receives precipitation during both the winter and the summer months but it is dry throughout. Region 2, the southwest corner, also receives precipitation throughout the year, but has a maximum from July to October. Region 3 is mainly mountainous and receives more precipitation in the summer months than in the winter months. The annual precipitation of the stations in Region 3 are not as homogeneous as one would like; this region includes a few front-range stations which individually display a distribution characteristic of the plains. Exclusion of these stations would show a

TABLE 5

LIST OF STATIONS IN EACH REGION

STATION NAME	ELEVATION IN FEET	AREA IN 10^5 ACRES
Region 1		
Artesia - Dinasaur National Monument	5,921	18.1
Craig	6,285	15.1
Grand Junction	4,855	23.1
Great Divide	7,030	12.5
Meeker	6,242	14.5
Rifle	5,400	11.3
TOTAL		94.6
Region 2		
Cedaredge	6,175	11.7
Durango	6,550	12.4
Mesa Verde	7,070	8.3
Ouray	7,740	7.3
Pleasant View	6,860	15.5
Silverton	9,322	6.8
Telluride	8,756	10.3
Wilcox Ranch	5,960	9.0
TOTAL		81.3
Region 3		
Allenspark	8,500	5.8
Aspen	7,928	5.8
Boulder	5,400	2.8
Climax	11,300	6.7
Eagle FAA	6,497	14.5
Elk Creek	8,430	4.7
Evergreen	7,000	2.7
Fort Collins	5,001	8.2
Grand Lake	8,288	12.1
Hartsel - Antero Reservoir	8,866	7.5
Hot Sulphur Springs	7,800	16.5
Longmont	5,145	3.5
Morrison	6,000	1.6
Sugar Loaf Reservoir	10,000	6.4
Woodland Park	7,760	2.9
TOTAL		101.7

Table 5. - Continued

STATION NAME	ELEVATION IN FEET	AREA IN 10^5 ACRES
Region 4		
Alamosa	7,536	8.2
Coaldale	6,525	11.9
Cochetopa Creek	8,000	7.9
Crested Butte	8,855	5.2
Cripple Creek	8,500	4.6
Gunnison	7,664	5.7
Lake George	8,500	3.9
Manitou Springs	6,606	3.4
Monte Vista	7,667	11.0
Mule Shoe Lodge	8,890	9.3
Saguache	7,697	9.1
San Luis	7,965	5.2
Tercio	8,040	4.4
Wagon Wheel Gap	8.500	17.8
TOTAL		107.7
Region 5		
Akron	4,538	13.2
Briggsdale	4,875	6.7
Burlington 12	4,230	7.0
Byers	5,233	3.5
Castle Rock	6,205	2.2
Deertrail	5,183	5.0
Denver AP	5,283	3.9
Denver City	5,221	1.8
Eckley	3,900	9.3
Greeley	4,648	5.4
Greenland 9	7,350	2.2
Greenland 7	6,820	1.1
Hoyt	4,995	8.0
Hugo	5,034	7.8
Joes	4,200	6.4
Kiowa	6,350	3.0
New Raymer	4,783	12.9
Nunn	5,185	4.4
Paoli	3,898	14.9
Parker	6,300	2.6
Seibert	4,703	8.3
Shaw	5,167	7.9
Simla	6,020	4.5
TOTAL		142.0

Table 5. - Continued

STATION NAME	ELEVATION IN FEET	AREA IN 10^5 ACRES
Region 6		
Arapahoe	4,013	8.8
Big Spring Ranch	6,035	5.4
Cheraw	4,082	8.4
Cucharas Dam	5,995	4.8
Eads	4,215	10.3
Forder	4,739	7.9
Fountain	5,546	4.6
Granada	3,484	11.8
John Martin Dam	3,814	8.5
Kim	5,240	14.6
Kutch	5,390	4.5
Pueblo AP	4,684	9.5
Springfield	4,405	15.1
Trinidad - Hoehne	6,030	10.4
Walsenburg	6,221	4.9
White Rock	4,750	10.0
TOTAL		139.5

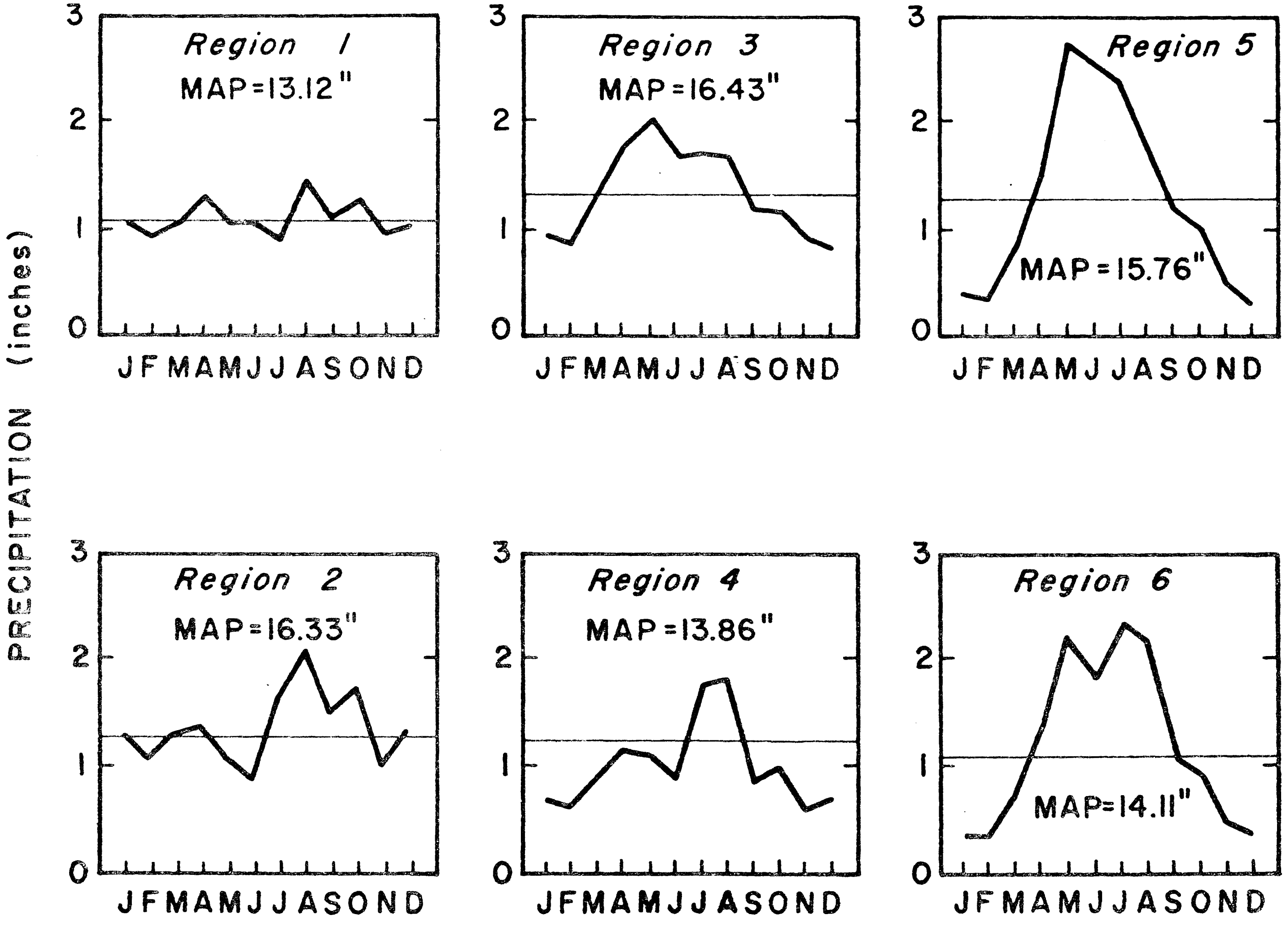

Figure 5. Monthly precipitation values of the six regions. M.A.P. is the mean annual precipitation. The mean monthly values are also shown.

much larger second peak in July. Region 4 is the San Luis Valley which has a monthly mean precipitation distribution similar to Region 2. Regions 5 and 6 have dry winters and receive most of their precipitation in the summer as is typical of the plains.

It is well known that altitude affects the amount of precipitation received annually (Landsberg, 1969), but this effect varies with different mountain ranges. Marlatt and Riehl (1963) showed that the variations of average annual precipitation due to elevation cannot be shown to be statistically significant for individual stations. In his report, Henry (1919) showed that precipitation increased with height for a series of stations at different elevations at two locations in the Utah-Colorado area. He concluded the orientation of a mountain range must be at an angle to the airflow to cause the air mass to ascend. A mountain range parallel to the windflow causes little or no increase in precipitation. Precipitation increases are also dependent on the steepness of the slope, the temperature and wetness of the air mass before ascent and the speed of the storm.

The variation of elevation and volume can be seen among the regions. Returning to Figure 4, the Continental Divide begins at the top of Region 3 then turns eastward and down the eastern part of the region. It then turns westward and runs along the border of Regions 2 and 4. As shown in Figure 5, Regions 2 and 3 have the highest mean annual precipitation. This may be explained by the fact that since the mountain range runs along the east side of Regions 2 and 3, the westerly flow, the high elevation and large elevation change create an upslope situation which increases precipitation. This precipitation increase causes many individual stations west of the Continental Divide to have large winter precipitation which exceeds their summer precipitation. The lower precipitation in Region 1 may be attributed to lower elevations. The west side of Region 4 lies to the leeward slope of the Continental Divide so the precipitation would be lower. When the storm containing Pacific moisture reaches the second range along the east side of the region, it would be drier than it was before crossing the Continental Divide; so the total precipitation in the area is less than that of Regions 2 or 3. Regions 5 and 6 are the eastern high plains with no mountain ranges to affect their precipitation.

4. STORM ANALYSIS

All precipitation events were included in the formation of storm events. The storms were partitioned into categories by their volume.

The histogram of the frequency distribution and the total volume yielded for each volume interval averaged over all regions are presented in Figure 6. The volume category is shown in the horizontal axis. The average value was used because all regions display approximately the same distribution over the categories. The values shown on the figure were adjusted because the intervals among categories vary. 196 storms have volumes greater than or equal to 0.1×10^5 acre feet but less than 0.15×10^5 acre feet. The total volume of water contributed by these 196 storms is 24.2×10^5 acre feet. As the storm size increases, the frequency decreases very rapidly, but the total volume increases until the storm size reaches 0.5×10^5 acre feet, then it begins to drop off very slowly.

To find a relationship between the two parameters, the volume and frequency occurring in each category were accumulated beginning from the largest category. Each accumulated value was then divided by its respective total to find the percentage accumulated up to that category. The cumulative percentage of volume versus frequency averaged over all the

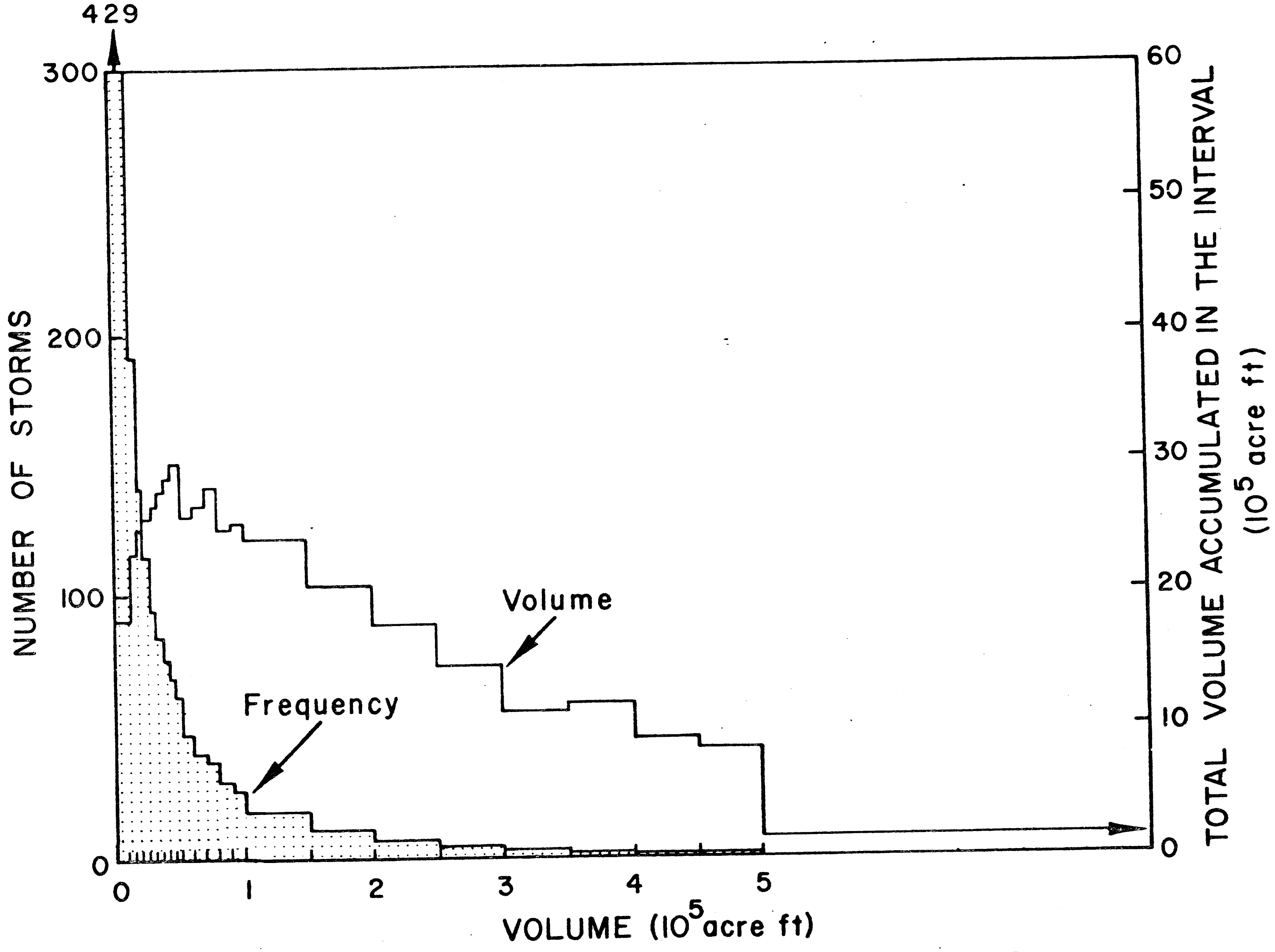

Figure 6. Histogram of the number of storms and the total volume in each volume interval averaged over six regions.

regions is shown in Figure 7. Eighty percent of the storm volume is contributed by the largest 30 percent of the storm occurrences and 50 percent of the volume by about 10 percent of the storm events. In his analysis of Argentine rainfall, Olascoaga (1950) used daily precipitation data and obtained a similar curve.

The curve in Figure 7 has very small slope at the lowest volume percentages and then increases very sharply. The point where volume is 83 percent was picked as the turning point because the curve appears to be fairly symmetrical there. This point was taken as the "noise level" where the largest categories which made up 83 percent of the total volume would be included in the analysis. They shall be referred to as significant storms. Even though about 70 percent of the storms would be ignored, the total volume included is sufficiently large to represent the precipitation regime.

To determine the validity of this "noise level", the total monthly volume was summed for four volume percentages: 100, 95, 83 and 55 percent. The monthly distribution of these volume percentages is shown in Figure 8. The 83 percent curve displays the monthly characteristics of each region well enough to represent the precipitation regime.

4.1 Storm Characteristics

Referring to the significant storms (83 percent) in Figure 8, there are two distinct maxima for all regions except Region 5; one occurs in spring around March-May, and another in July and August. The maximum precipitation in early spring usually comes in the form of snow associated with large scale systems. It is a transitional period between winter and summer where the general circulation still retains some wintertime characteristics but obtains enough moisture from the Gulf of Mexico to

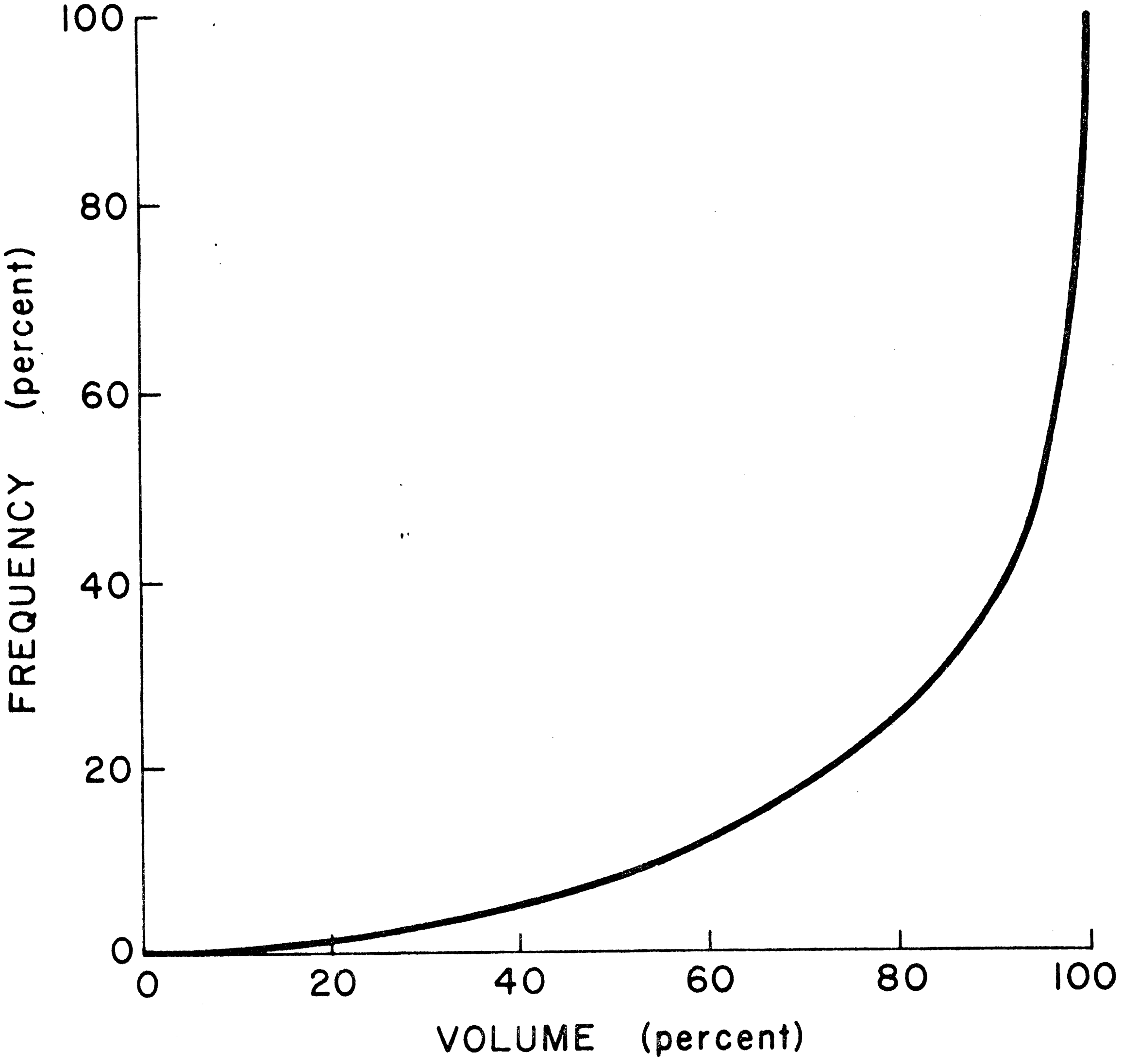

Figure 7. Relation between cumulative percent frequency distribution of storms against cumulative percent storm volume. Large size storms are cumulated first.

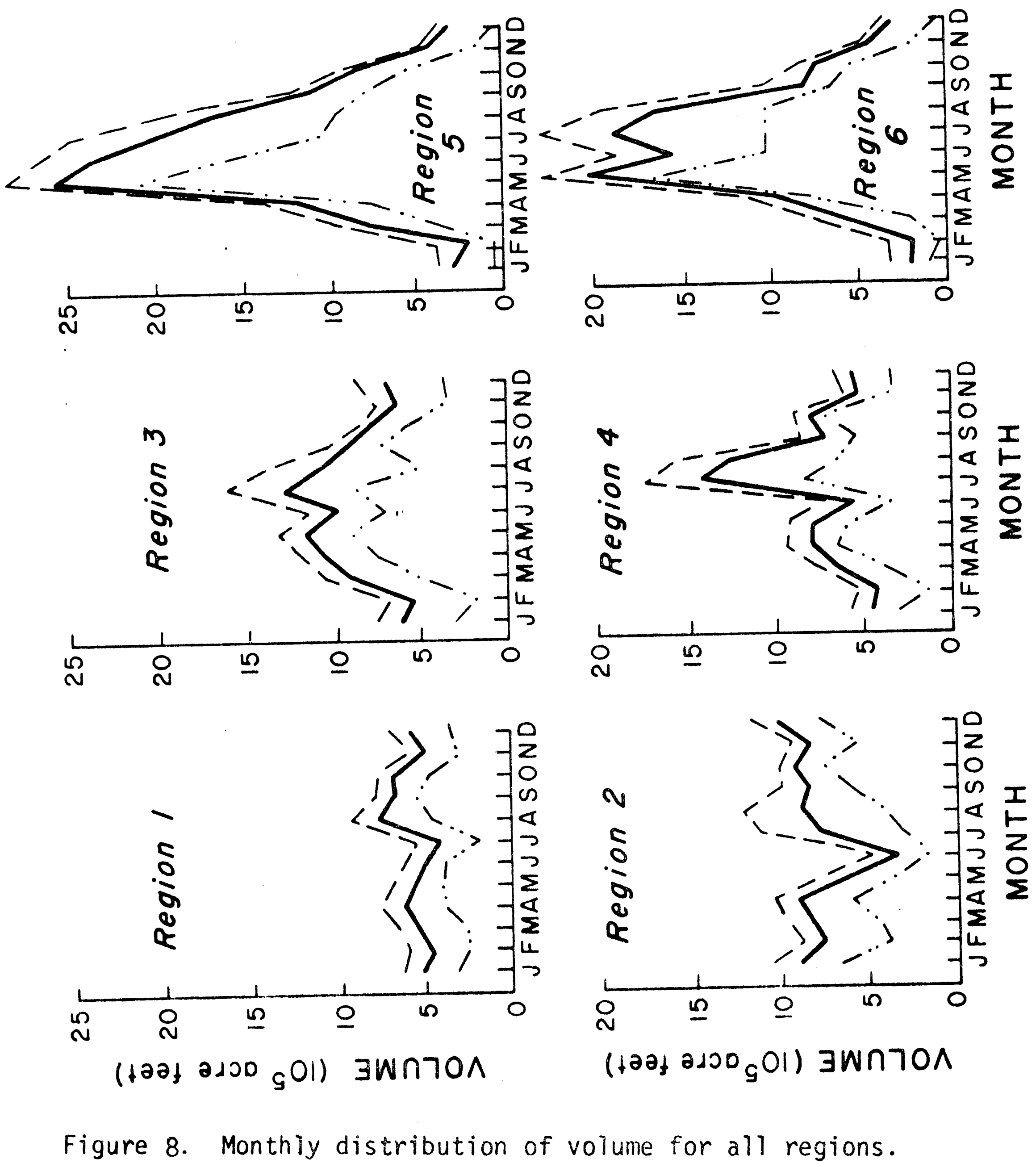

Figure 8. Monthly distribution of volume for all regions.

— — — — — — 100% of all storms

———————— 83% of all storms (significant storms)

—··—··—·· 53% of all storms

precipitate heavily over a wide area. In late summer, the precipitation maximum is associated with thunderstorm activity. Regions 5 and 6 are the eastern plains with approximately the same rainfall characteristics of dry winters and wet summers. Region 5 has more precipitation than Region 6, and there is only one summer maximum as compared with two in Regions 6. This maximum in Region 5 occurs in May and lasts through August. In Region 6, the first maximum occurs in May followed by a minimum in June, then another maximum of approximately the same magnitude occurs in July and August.

4.2 Seasonal Comparison

A time series of annual, winter and summer precipitation volume for 1952-1970 is shown in Figure 9 for each region. Here the precipitation year begins in October of the previous calendar year and continues through September. The annual volume is better correlated with the summer volume than with the winter volume. This correlation is illustrated by the summer curves in Figure 9 where wet summers coincide with wet years. In Region 2, the winter-annual correlation coefficient is 0.63. It is only eight percent below the summer correlation coefficient. Wet winters occurred for this region in 1952, 1958 and 1969. In 1952 and 1969, the annual values agreed with the winter value; whereas in 1958, the wet winter only compensated for the dry summer to yield an average year. The winter precipitation in Region 2 contributes 54 percent of the annual total precipitation. In the other regions, the summer months contribute more water to the annual total than do the winter months. The difference between the two seasonal correlation coefficients becomes correspondingly larger.

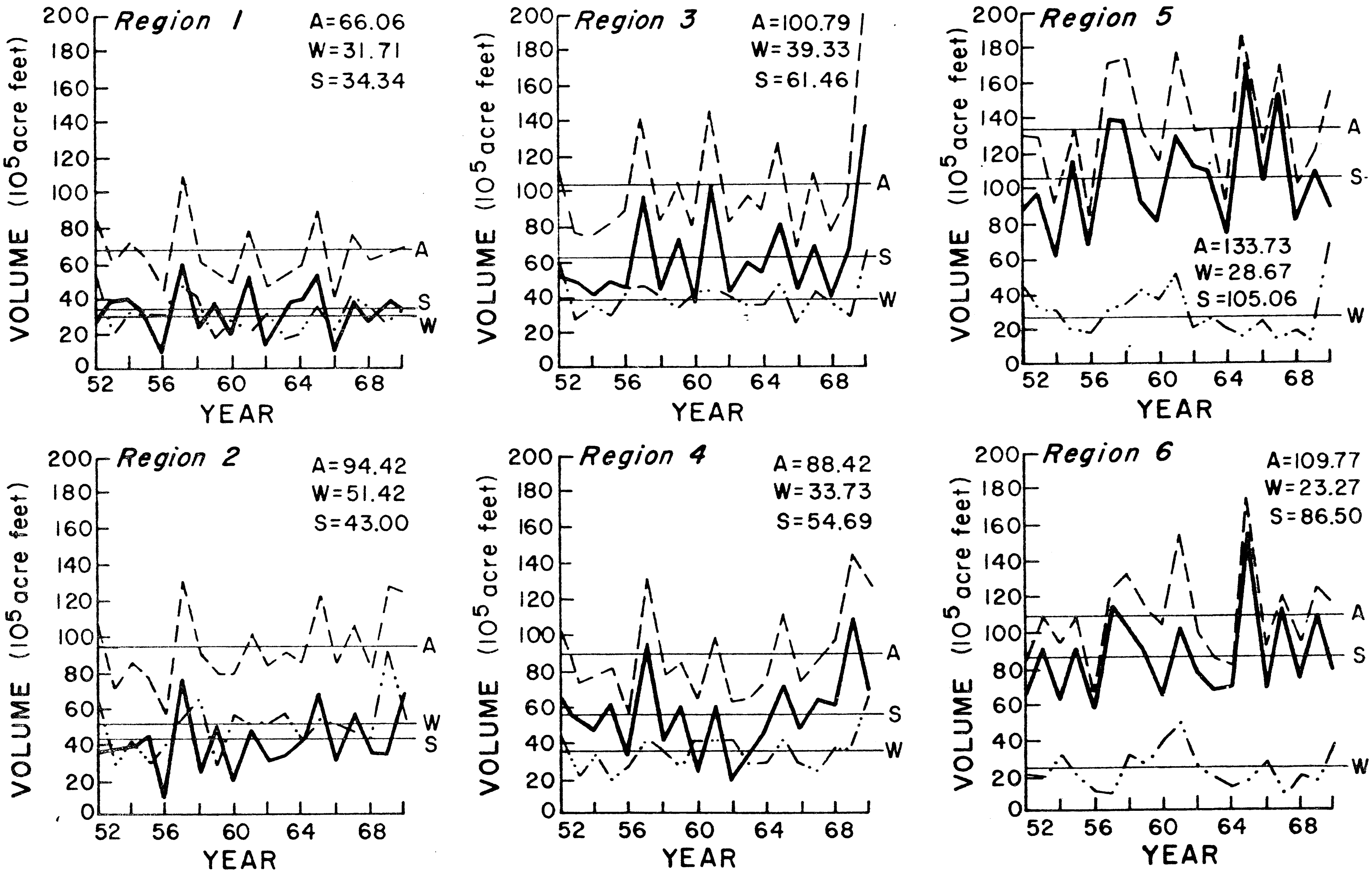

Figure 9. Time series of the annual and seasonal total volume of 19 water years, 1952-1970.
A = Average
W = Winter
S = Summer

The coefficient of variation is used to measure the relative variability of precipitation. Referring to Table 6, the coefficients of variation in Regions 5 and 6 are lower for summer than winter where summer precipitation accounts for 80 percent of the annual volume. This low coefficient of variation for Regions 5 and 6 in the summer is primarily due to the large total summer precipitation volume. In the other regions, the coefficient of variation is lower for the winter season. The summer volume is 40 percent of the annual total in Regions 3 and 4 and 50 percent in Regions 1 and 2. This suggests that the winter precipitation is less variable than summer precipitation. It also appears that the seasonal precipitation is more homogeneous in the north-south direction than in the east-west.

In spite of this north-south agreement among regions in the seasonal variation, the difference between winter and summer correlation coefficients is in better agreement in the east-west direction. The difference in correlation coefficient is 0.24 in Regions 1 and 3 and 0.37 in Regions 4 and 6. A possible explanation for this agreement is that the storm track moves across Colorado in an approximate east-west orientation so that the storms affect the laterally adjacent regions in the same manner while reflecting the topographic characteristics of each region.

4.3 Event Analysis

In order to determine how storms of different yield affect the annual precipitation, storms were divided into five categories according to size. These categories are the same as those used by Riehl and Elsberry (1964). The percentage of the volume in each class is shown in Table 7. Classes 1 and 5 yield approximately the same amount of water, about 14 percent of the total volume, and class 3 contributes twice that amount. The actual

TABLE 6

COMPARISON OF VOLUME STATISTICS BETWEEN SEASONS.

REGIONS	1	2	3	4	5	6
WINTER						
$\bar{v}$ in 10^5 acre ft.	31.71	51.42	39.33	33.73	28.67	23.27
SD in 10^5 acre ft.	9.41	14.85	10.48	10.44	13.95	11.49
CV	.30	.29	.27	.31	.49	.49
% of Annual Precip.	48	54	39	38	21	21
r	.58	.63	.73	.53	.28	.56
SUMMER						
$\bar{v}$ in 10^5 acre ft.	34.34	43.00	61.46	54.69	105.06	86.50
SD in 10^5 acre ft.	13.92	16.32	26.08	21.67	29.74	24.84
CV	.41	.38	.42	.40	.28	.29
% of Annual Precip.	52	46	61	62	79	79
r	.83	.71	.96	.91	.89	.92
ANNUAL						
$\bar{v}$ in 10^5 acre ft.	66.06	94.42	100.74	88.42	133.73	109.77
SD in 10^5 acre ft.	17.04	20.99	32.69	25.29	30.39	25.54
CV	.26	.22	.32	.29	.23	.23
$r_{sum}-r_{win}$	.25	.08	.23	.38	.61	.36

$\bar{v}$ is the average volume for the season

SD is the standard deviation

CV is the coefficient of variation given by $\frac{SD}{\bar{v}}$

r is the correlation coefficient between the seasonal and the annual volume.

TABLE 7

CLASSIFICATION OF STORMS

CLASS	% OF VOLUME	% FREQUENCY	Volume categories in 10^5 acre feet for each region					
			1	2	3	4	5	6
1	.13	2	≥5.4	≥8.0	≥6.8	≥7.0	≥12.5	≥12.5
2	.22	9	5.3-2.7	7.9-4.4	6.7-4.0	6.9-3.8	12.4-7.2	12.4-6.5
3	.28	21	2.6-1.5	4.3-2.5	3.9-1.9	3.7-1.8	7.1-3.5	6.4-3.2
4	.23	29	1.4-0.9	2.4-1.4	1.8-1.0	1.7-1.0	3.4-1.7	3.1-1.7
5	.14	39	0.8-0.0	1.3-0.0	0.9-0.0	0.9-0.0	1.6-0.0	1.6-0.0

storm class varies for each region as shown in Table 7. In Table 8, the number of storms that occurred in each category, the total volume and frequency and the average frequency for the driest and wettest five years averaged over the six regions are shown. In the last two lines of the table, it is shown that the driest quartile has two to three storms fewer than the wettest quartile for each of the categories; therefore, there does not appear to be a preferred storm size which is absent in a dry year. The omission of storms in a dry year appears to be approximately uniformly spread among all size categories.

The values in Table 8 were averaged over the six regions, thus smoothing out any irregularities in the frequency distribution. The actual frequency of storms over the categories from Region 6 is shown in Table 9. The third wettest year, 17, had 50 storms compared to only 38 storms for the wettest year, 19. Referring back to Table 7, five or six small class 5 storms are needed to compensate for the volume due to the lack of occurrence in large class 1 storms; whereas only two or three are needed to compensate for a medium size class 3 storm. Year 17 did not have any class 1 storms, but it was compensated by the frequent occurrences in classes 3, 4 and 5 whereas year 11 had only 20 storms, ten storms fewer than its neighboring rank. Year 11 had its share of large storms, yet lacked in the lowest three categories. Therefore, the annual volume is dependent on both the number of storms and the distribution of these storms among the yield categories.

Riehl and Elsberry found that the greatest contribution to the rank order of the annual precipitation total is obtained from the middle three classes of storms. The volume of precipitation contributed by the smallest storm categories is almost consistent at 13 percent for all years.

TABLE 8

FREQUENCY OF STORMS BY CATEGORY FOR EACH YEAR AVERAGED OVER ALL REGIONS RANKED BY VOLUME.

Year	Annual Storm Volume 10^5 acre feet	Class Number and Percent Frequency in Each Class					Total Number of Storms
		1	2	3	4	5	
		13%	22%	28%	23%	14%	
1	62	0	2	6	10	13	31
2	70	0	2	8	10	14	34
3	73	1	1	7	12	14	36
4	76	0	2	8	14	12	36
5	82	1	3	7	14	12	37
6	84	1	3	9	11	15	38
7	87	1	3	9	12	16	40
8	89	0	3	9	14	16	42
9	91	0	5	8	14	14	41
10	93	1	3	10	13	15	41
11	96	2	3	7	11	14	37
12	98	1	4	8	13	14	41
13	104	2	4	8	14	13	41
14	110	1	5	11	13	12	41
15	116	2	4	10	16	14	45
16	123	2	5	10	14	14	45
17	130	2	4	11	16	16	50
18	138	3	5	13	14	16	50
19	157	3	9	9	15	15	51
	Average frequency driest five years	.4	2	7.2	12	13	
	Average frequency wettest five years	2.4	5.4	10.6	15	15	

TABLE 9

FREQUENCY OF STORMS BY CATEGORY FOR EACH YEAR RANKED BY VOLUME FOR REGION 6

Year	Annual Storm Volume 10^5 acre feet	Class Number and Percent Frequency in Each Class					Total Number of Storms
		1	2	3	4	5	
		13%	22%	28%	23%	14%	
1	67	0	2	3	6	13	24
2	82	1	0	3	11	12	27
3	85	1	1	6	12	9	29
4	86	1	1	4	14	7	27
5	93	0	2	8	14	4	28
6	94	0	3	10	4	10	27
7	94	1	3	6	7	9	26
8	100	0	3	6	13	16	38
9	105	0	4	7	13	9	33
10	110	0	3	11	9	14	37
11	110	1	3	7	4	5	20
12	114	1	4	8	7	12	32
13	115	0	4	8	14	9	35
14	121	0	4	11	11	12	38
15	124	2	3	6	13	11	35
16	125	2	3	4	14	14	37
17	134	0	2	9	18	21	50
18	154	2	3	12	11	17	45
19	173	2	6	4	8	18	38
	Average frequency driest five years	.6	1.2	4.8	11.4	9	
	Average frequency wettest five years	1.8	3.4	7	12.8	16.2	

Any difference in volume resulting from this class may easily be compensated by other classes (see year 11, Table 9). The occurrence of a large, class 1 storm would definitely increase the annual volume, but its average frequency for the wettest quartile is only 2.4 per year which may easily be compensated by five to eight storms from class 4 or three to four storms from class 3. Therefore, this confirms that the sum of the middle three categories is the most stable indicator of the "wetness" of a certain year; the middle three categories account for an average of 70 percent of the annual precipitation.

The cumulative volume and frequency relationship for all the significant storms is shown in Figure 10, curve A. The same relationship is shown in curve B as found by Olascoaga (1950) in his analysis of Argentine rainfall and in curve C by Riehl and Elsberry's (1964) analysis of the upper Colorado River Basin. These three curves agree with each other quite well. As Olascoaga pointed out, this relationship is independent of geography and rainfall regime, i.e., the percent of storms yielding the middle 70 percent of the total volume is approximately the same independent of geography. Therefore, this middle 70 percent would also best indicate the "wetness" of a year for all regions in Colorado, and other locations where the same graph holds true.

5. APPLICATIONS

This report presents background precipitation data for the state of Colorado as a whole and for six subregions. These data will be useful for the following applications. They provide a detailed description of the meteorological regimes responsible for the annual precipitation. They provide a data base for Colorado land and resource planning and establish that there is no significant long-term statewide precipitation

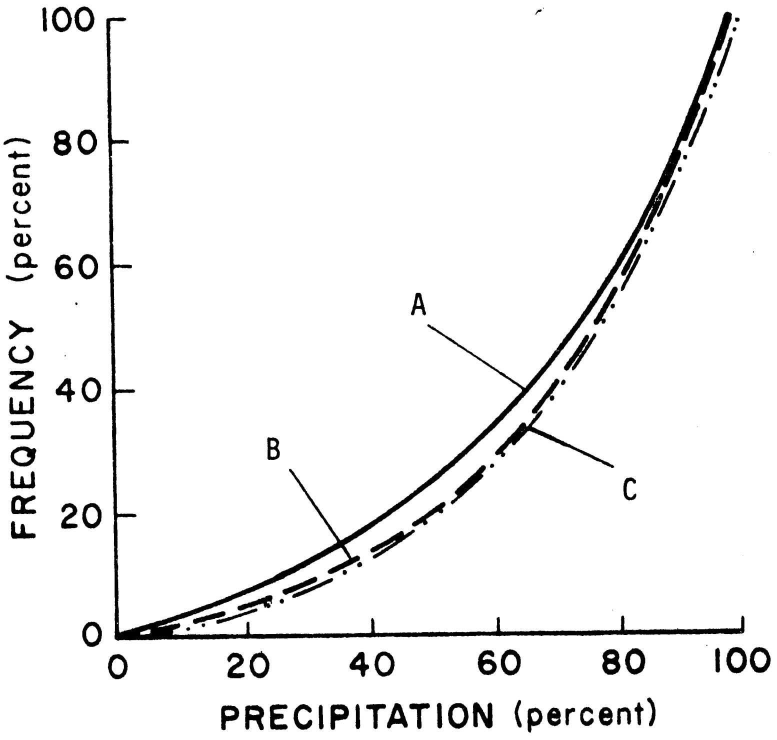

Figure 10. Percent cumulative storm volume versus percent cumulative storm frequency.

trend. Already, J. Michael Sinton, a water resource engineer, and Harold W. Steinhoff, the southwest regional administrator of the CSU Cooperative Extension Service, have shown keen interest in the results of this project.

6. SUMMARY

It was found that no statistically significant trend, in the statewide precipitation for a 56 year period could be detected. When data from adjacent stations were analyzed, it showed that single station precipitation data may be used to realistically represent an area average precipitation value. The characteristics of precipitation events of different sizes were computed and analyzed in detail from a 20 year set. The annual precipitation of Colorado is produced by large scale disturbances in the winter and by thunderstorms in the summer, and 80 percent of the precipitation volume is produced by 30 percent of the storm occurrences. The average storm duration is greater for the mountainous regions, and the volume of precipitation in the summer is better correlated with the annual volume than is the winter volume in all regions.

REFERENCES

Draper, N. R. and H. Smith, 1966: Applied Regression Analysis. John Wiley and Sons, In.

Henry, A. J., 1919: Increase of Precipitation with Latitude. Mon. Wea. Rev., 47, pp. 33-41.

Landsberg, H., 1969: Physical Climatology. 2nd Edition. Gray Printing Company, Inc. DuBois Pennsylvania, 446 pp.

Marlatt, W. E. and H. Riehl, 1963: Precipitation Regimes Over the Upper Colorado River. J. Geophys. Res., Vol. 68, No. 24, pp. 6447-6458.

Olascoaga, M. J., 1950: Some Aspects of Argentine Rainfall. Tellus, 2, (4), pp. 312-318.

Riehl, H.,and R. L. Elsberry, 1964: Precipitation Episodes in the Upper Colorado River Basin. Pure and Appl. Geophys., 57, pp. 213-220.

Sellers, W. D., 1960: Precipitation Trends in Arizona and Western New Mexico. Proceedings of the 28th Annual Snow Conference, Santa Fe, New Mexico, pp. 81-94.