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DISTRIBUTION OF PRECIPITATION ON RUGGED TERRAIN IN CENTRAL ARIZONA

by

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ABSTRACT

A 3-year study was conducted using tilted, vertical, directional, and recording rain gages (52 in all) to evaluate rainfall distribution on the Three Bar experimental watersheds in central Arizona. The tilted gages did not improve the determination of mean areal precipitation on the small watersheds because about as many tilted gages caught less rain as caught more. Although rugged and steep, the local topography exerted only minor effects on rainfall distribution compared to the major influence exerted by the Mazatzal Mountains to the windward (southwest). Forty-nine percent of wind travel was from the southwest quarter and wind averaged 4.4 mph when rain was actually falling. Wind exceeded 10 mph 9 percent of the time and 15 mph 0.4 percent of the time. Mean annual precipitation on the 600-acre study area ranged from 30 inches at 5,000 feet elevation to 22 inches at 3,400 feet (5 inches per 1,000 feet). Results of this study indicate that precipitation averages about 36 inches at 6,200 feet elevation along the Mazatzal crest near Four Peaks, about 6 inches more than published data show for the site.

INTRODUCTION

A late winter storm in April, 1976 dropped about an inch of rain in the Phoenix area and 3 inches in Payson, some 75 miles to the northeast. Other official weather stations in the central Arizona highlands reported intermediate amounts. Elevation was an obvious factor, though not the only one, affecting the amounts received. Other less easily measured factors, such as wind blowing over uneven terrain, can materially alter the distribution of rain and snow in mountain areas. An example of how rainfall can vary on steep terrain is available for the April storm on the Three Bar experimental watersheds, located roughly midway between Phoenix and Payson on the northeast slopes of the Mazatzal Mountains near Four Peaks. Rainfall varied from 3.41 inches at 3,300 feet elevation to 4.14 inches at 5,150 feet elevation, the upper gage catching 21 percent more rain than the lower gage. The gages are 1.6 miles apart.

Most reporting stations in the central highlands at elevations similar to or higher than Three Bar caught much less rainfall. The Three Bar area appears to be one of the wettest places gaged in Arizona within the elevation range of 3,300 to 5,200 feet. Mean annual precipitation ranges from 22 inches at 3,400 feet to 30 inches at 5,000 feet elevation.

Mountainous terrain presents special problems in measurement of precipitation. Many gages would be required, often in inaccessible sites, to adequately sample the highly variable distribution patterns. For expediency, however, rain gages are often located along travel routes, and mountain tops are sometimes gaged where access is provided for other purposes. While these arrangements may be the only practical way to get estimates of precipitation in remote areas, the results can be misleading if the problems associated with the rainfall measurements are not taken into account. Mountain tops and prominent ridges make poor gaging sites because strong winds reduce gage catch. Gages in exposed sites can be fitted with shields to reduce wind effect, but shielding alone does not insure an accurate catch, especially of snow. Because of these deficiencies, the distribution of precipitation in rugged terrain is seldom well defined, and the amount received at high elevations is often underestimated.

Because of uncertainty about variability of precipitation on the Three Bar experimental watersheds, a dense network of rain gages was installed in 1968 to evaluate the distribution of rain on the steep slopes of these small catchments. The Three Bar study area is located between the Tonto arm of Roosevelt Lake and the Mazatzal Divide about 8

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miles to the southwest (fig. 1). Watershed management and game management research have been conducted by the U. S. Forest Service and Arizona Game and Fish Department in the area since the early 1950's.

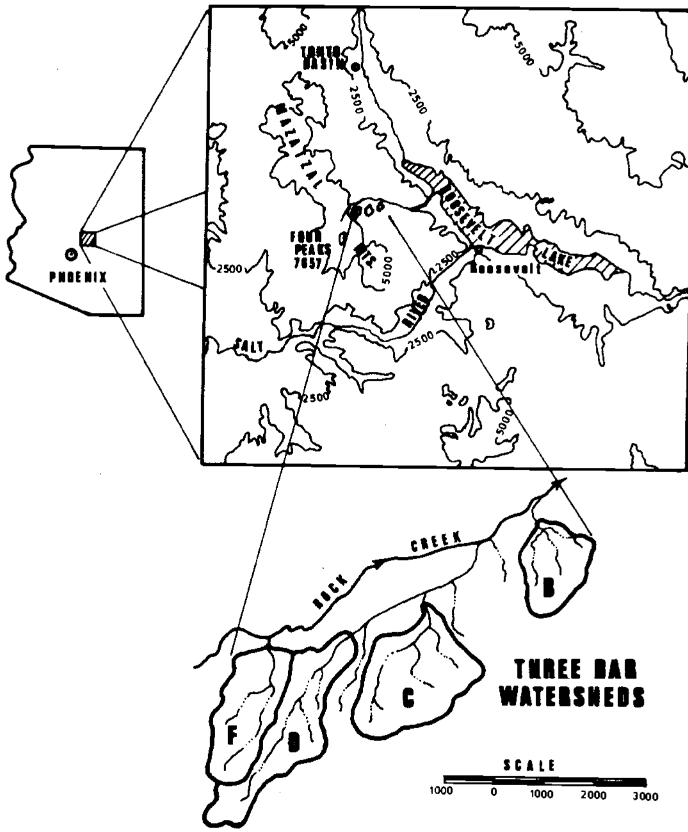

Figure 1. The Three Bar experimental watersheds lie on the eastern slopes of the Mazatzal Mountains between Four Peaks and Roosevelt Lake in central Arizona.

Four small chaparral-covered watersheds (46 to 95 acres) and intervening spaces comprise the study area of about 600 acres. The topography is steep and broken (fig.2). Extremes in elevation range from 3,300 feet on Watershed B to 5,250 feet on D. The distance between these points is 8,700 feet for an average gradient of 22 percent. Individual watersheds are even steeper; average gradients vary from 26 percent on C to 43 percent on F. Slopes are steepest in the upper portions of the watersheds, where they sometimes exceed 70 percent. There is a pronounced tendency for rainfall to increase with elevation. The catch at the top of Watershed D averages almost 40 percent greater than at the bottom of Watershed B.

PROCEDURES

A total of 52 precipitation gages at 27 locations were operated over a 3-year period to get the data used in this study. All gages had 8-inch-diameter orifices installed 3 to 4 feet above the ground (fig. 3) except where otherwise noted. Twenty-two of the gages were installed in the standard vertical position (orifice horizontal);

Figure 2. Chaparral covered Three Bar watersheds (B is out of sight to left) showing location of site C7/C6 and the climatic station near the stream gage.

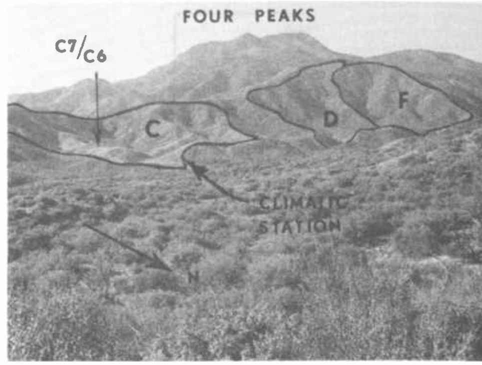

Figure 3. Instrumentation at site C7/C6 on intermediate ridge in lower, central watershed C. Instruments from left to right: vertical and tilted rain gages, wind direction indicator, shielded rain gage, directional rain gage (vectopluviometer) with cup anemometer mounted on top, and recording rain gage (weighing type). Both wind speed and direction were continuously recorded on a strip chart.

five of these were equipped with Alter wind shields designed to reduce distortion of catch caused by wind turbulence around the gage orifice. Three of the shielded gages were mounted on towers 6 to 10 feet high. Another 22 gages were installed so that they tilted normal (orifice parallel) to the slope of the hillside where they were located. Tilted and vertical gages were paired at 13 sites to evaluate differences in catch due to tilting. Directional rain gages (vectopluviometers) were installed at five of these sites to determine the direction of wind and inclination of rainfall, an index of wind speed. Recording rain gages were located at three sites to determine rainfall intensity. In addition, wind direction and speed were continuously recorded at the C7/C6 site in lower, central watershed C (figs. 2 & 3).

The watersheds were divided into facets (fig. 4) by visually selecting areas of relatively uniform slope and aspect on a detailed map with 10-foot contour intervals. Constraints on numbers of gages and difficulty of access in some areas resulted in fewer gages in portions of watersheds D and F than in C and B. Nine gages which had been installed years before were used even though their locations did not necessarily fit the prescription. A tilted gage was installed in each facet except at D-4 and at each of the four stream gaging sites. Each tilted gage was installed so that its direction and tilt were the same as the average aspect and slope of the facet in which it was placed. The aspect and slope were determined first from the contour map and later verified and modified as necessary from measurements taken in the field with hand-held abney level and compass.

Tilting the gage gives a more accurate measure of precipitation reaching the sloping hillside than does a vertical gage whenever wind causes rain drops to be inclined from the vertical (Hamilton 1954, Corbett 1967, Jackson and Aldridge 1972, and Sevruk 1974). The difference in catch between vertical and tilted gages depends on degree of tilt, wind direction, and wind velocity. Vertically falling rain is measured equally well by either gage, as is rain driven by wind at right angles to the direction of tilt. The actual catch of tilted gages must be corrected by dividing the catch by the cosine of the angle of tilt to account for reduction in orifice area (as projected to a horizontal surface) caused by tilting (Hamilton 1954).

The vectopluviometer is designed with four vertical orifices at right angles to each other, each facing a cardinal direction (fig. 3). Only inclined rainfall

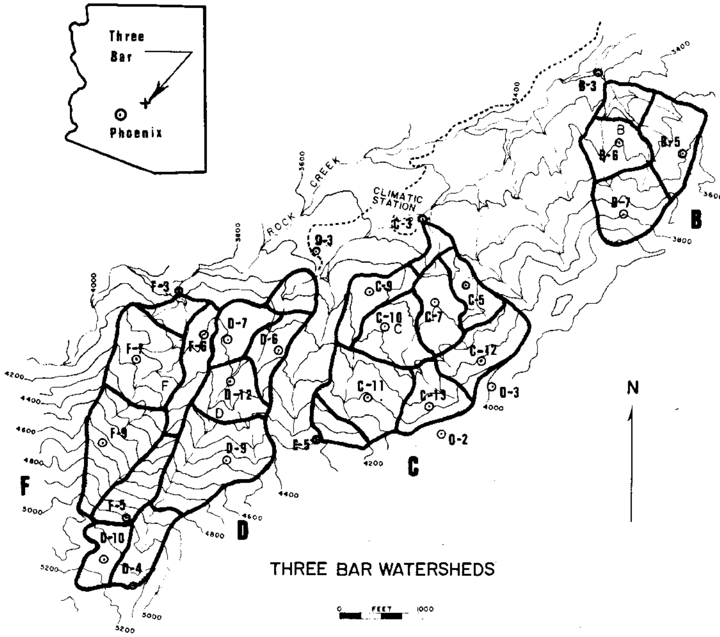

Figure 4. Refined facet breakdown with one tilted gage in each facet except that gages B-3, C-3, D-3, F-3, and D-4 are vertical only.

(horizontal component) can enter these orifices. Vertically falling rain must be caught in an adjacent, standard gage. The amount caught in each of the vectopluviometer openings is indicative of the direction and force of wind during rainfall. According to Hamilton (1954), average storm direction (ω) and angle of inclination of rain from the vertical (i) are found by

$$\omega = \arctan \frac{E - W}{N - S} \tag{1}$$

$$i = \arctan \frac{N - S}{R \cos \omega} \tag{2}$$

where N, E, S, W are component catches of vectopluviometer quadrants and R is catch of an adjacent vertical gage.

Gages were read at intervals of 1 week to 4 months. In all, 21 readings (observations) were made during the 3-year period (July 1968 - June 1971). Bears were particularly attracted to the gages in early spring, presumably because of the oil added to prevent evaporation. Damage by bears resulted in loss of about 7 percent of the data. Statistical analyses were made on uninterrupted data only. For other purposes, missing data were estimated by double-mass plottings or by a ratio method using nearby gages.

TILTED VERSUS VERTICAL GAGES

Of 13 pairs of gages, 5 tilted gages caught more rain than vertical gages, 4 caught less, and 4 showed no significant difference. Some of the gages did not perform as anticipated, based on their orientation with respect to the indicated prevailing wind. Since 10 of the gages tilted away from the prevailing wind (table 1 and fig. 5), their catches should have been less than vertical gages. However, three of them (O3, C12, C13) actually caught more rain and 3 others were not significantly different from vertical gages. The probable explanation is that wind was modified by local topography sufficiently to cause the observed differences in catch.

Only at the five sites with vectopluviometers (fig. 5) was it possible to demonstrate how wind affects the catch of tilted and vertical gages. The vectopluviometers at B5/B8 and O2/O1 (table 1) indicated that wind blew against the tilt (the gage tilted into the hemisphere from which the wind came), which caused them to catch more rain

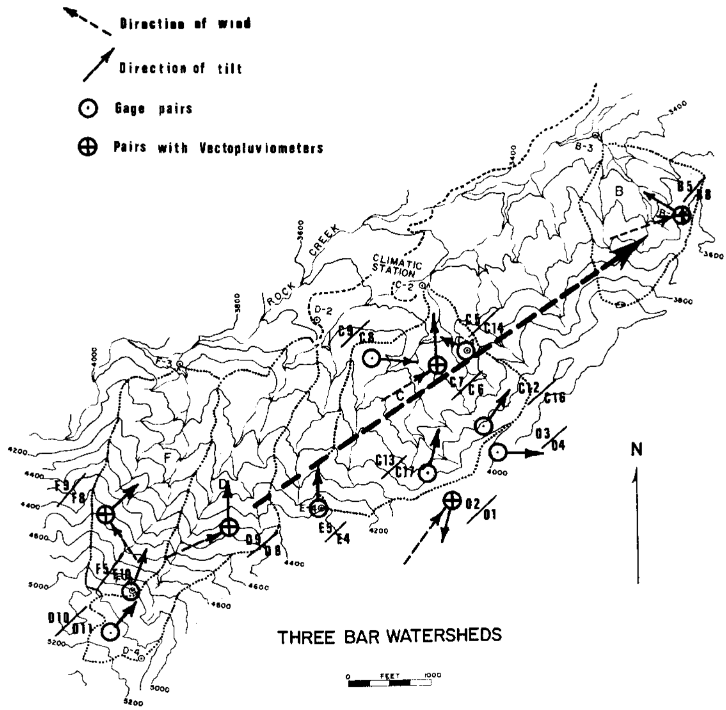

Figure 5. Solid arrows indicate direction of tilt for each of 13 pairs of gages. Broken arrows indicate direction of prevailing wind during rainfall at each of 5 sites with vectopluviometers. The large broken arrow indicates the weighted average direction obtained by combining all data from the five vectopluviometers.

than the vertical gages. The opposite was true at C7/C6 and D9/D8 where wind blew mostly with the tilt; these tilted gages caught less rain. The vectopluviometer at F9/F8 showed wind to be almost at right angles to the direction of tilt, and the catch difference at this site was not significant. Possibly, the lack of significance in the differences shown by the three other pairs of gages (C5/C14, F5/F10, D10/D11) may be explained in the same way. Tilted gages F5 and D10 at two of these sites face the same general direction and are immediately upslope from F9/F8. They could easily be affected by the same wind patterns observed at F9/F8.

It may be inferred from these results that tilted gages did not improve the determination of mean precipitation on the experimental watersheds, since about as many tilted gages caught less rain as caught more. For example, inclusion of 6 tilted gages (at paired-gage sites) had no significant effect on the estimate of total precipitation received on watershed C because 3 (C7, C9, E5) of the 6 tilted gages caught less rain while 2 (C12, C13) caught more rain (C5 was not significantly different) than adjacent vertical gages. Thus there was no advantage demonstrated by the tilted gages, except to illustrate how wind and topography can affect local distribution of precipitation within these small watersheds.

SHIELDED GAGES

Only one of the four shielded gages caught significantly more rain than its adjacent vertical gage. This gage (C15) was moderately exposed on an intermediate ridge at the C7/C6 site (figs. 2 & 3) where surrounding shrubs had been removed prior to the study. Without replication it is difficult to know if the combination of ridge exposure and lack of protective shrubs explain the higher catch by the shielded gage. However, because shields were designed to improve gage accuracy under conditions like these, it seems reasonable to assume that the shielded catch is the more accurate for the site. At the other less exposed sites, it appears that shields were not beneficial. Based on these limited results, shields should not be necessary where surrounding vegetation is at least as high as the gage orifice, and wind during rainfall is no greater than was found on these watersheds.

WIND DIRECTION AND INTENSITY

Wind prevailed from the southwest (fig. 6). By octants, 33 percent of total wind travel was from the southwest, 21 percent from the west, and 11 percent from the south. Nearly one-half (49%) of the wind was from the southwest quarter (180^o - 270^o). These wind measurements were made at the C7/C6 site (figs. 2 & 3), thought to be fairly representative of the watersheds generally. However, wind varies considerably because of local topography as illustrated by the following examples. Wind averaged 93 miles per day (3.9 mph) for 2 years at the C7/C6 site, but only 30 miles per day at the climatic station 1,000 feet to the north and 150 feet lower elevation near Rock Creek (fig. 2). The lower site is in a topographic depression and is partially protected by brush, while the upper site is moderately exposed on a grassy ridge. Also, a consistent diurnal pattern of wind movement prevailed most days on watershed C. Early morning wind is light and flows downslope, out of the south. About sunup the wind picks up and gradually switches direction until by midmorning it is moving upslope, out of the northeast. In the early afternoon the wind begins to shift back, and by midafternoon is out of the southwest. Here it remains until near midnight when speed diminishes and alters course slightly to be once more from the south.

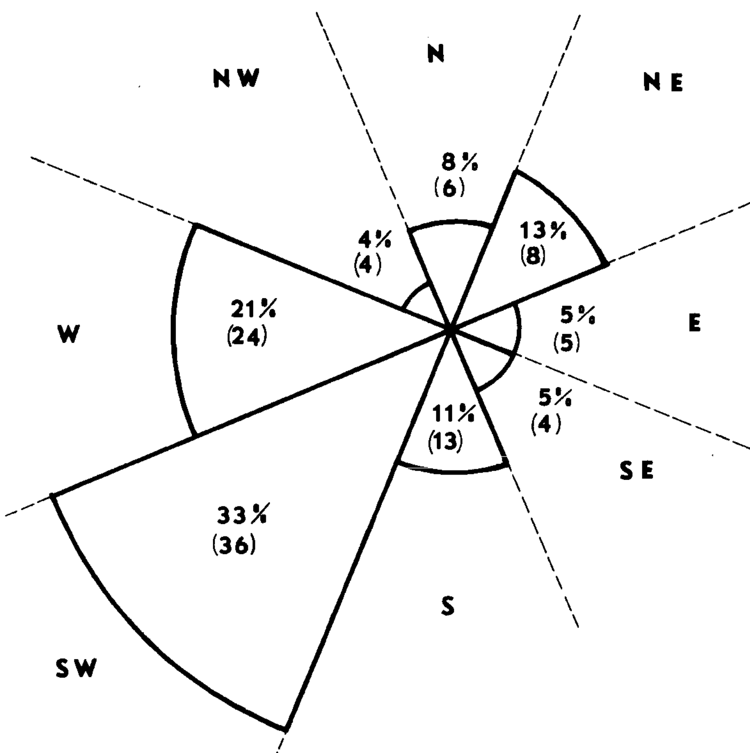

Figure 6. Wind prevailed from the west southwest. Numbers indicate percent of wind travel accounted for by each octant (parentheses indicate wind during rainfall).

To determine wind behavior during rainfall, 29 events were analyzed, including the heavy storm on Labor Day weekend 1970. During actual rainfall, wind direction was similar to non-rain periods, except that a greater percentage of the wind was from the southwest, west, and south octants (figures in parentheses in fig. 6). Also, average wind speed was slightly greater (13%) during rainfall than when it was not raining.

In the course of a year it actually rained less than 2 percent of the time, or about 25 minutes for each 24 hours on the average. The longest period of continuous rainfall was 21 hours, the shortest, a summer shower, 10 minutes. The longest rainless period lasted 67 days. The combined duration of the 29 rainfall events was 175 hours; during this time, 29 inches of rain fell, and wind averaged 4.4 mph. Wind exceeded 10 mph 9 percent of the time, and exceeded 15 mph 0.4 percent of the time. The higher wind speeds came during two summer convection storms when wind speed averaged 18.3 and 15.6 mph for 20 minutes each. Wind gusts were not analyzed separately, but no extremely high gusts were noticed while processing the records.

The 1970 Labor Day Weekend storm was considered a 100-year or greater event over much of central Arizona (Thorud and Ffolliott 1973). At the C7/C6 site, rainfall totaled 7.25 inches during 41 hours, which included some rainless intervals. Wind prevailed from the southwest during most of the storm, and averaged 5.8 mph during the 25 hours that rain was actually falling. The strongest winds occurred on the afternoon of the 5th and coincided with the most intense rainfall. Wind averaged 14 mph for 20 minutes while 0.63 inch of rain fell. A short time later, wind was equally strong for a full hour, although rain intensity had dropped to about one-third inch per hour.

Wind direction during rainfall (table 1) was also available from the vectopluviometers by use of equation 1. The mean wind direction indicated by the vectopluviometer at the C7/C6 site agreed very closely with the mean direction measured by the adjacent wind recorder. Wind at each of the five vectopluviometer sites (small broken arrows in fig. 5) was out of the southwest or west with the exception of the F9/F8 site on

Table 1. Direction and angle of tilt and mean difference in catch per observation between tilted (T) and vertical (V) gages arranged in order of increasing angle of tilt. Also included for sites with vectopluviometers are mean wind direction and mean inclination of falling rain.

Gage Pairs (T/V)	Aspect (Dir. of gage tilt)		Slope (Angle of gage tilt)		Mean difference in catch per observation		No. of observations	Level of Signif.	Mean 1/ Wind Dir. ($\bar{\omega}$)	Mean Inclination ($\bar{T}$)
	Deg. N. AZ	Octant	Deg.	%	Inches	% $\frac{100(T-V)}{V}$			Deg. N. AZ	Deg. from Vertical
C7/C6 2/	355	N	11.3	20	-.11±.15	- 3.7	20	.01	58	20
C9/C8	97	E	12.4	22	-.08±.06	- 2.6	20	.001		
C5/C14 3/	297	NW	16.7	30	.04±.15	1.7	20	ns		
D10/D11	42	NE	18.8	34	-.10±.25	- 2.7	18	ns		
B5/B8 2/ 3/	300	NW	23.3	43	.25±.25	10.4	21	.001	73	20
02/01 2/ 3/	195	S	25.2	47	.17±.17	6.2	15	.01	38	12
E5/E4	356	N	25.2	47	-.27±.03	- 6.9	18	.01		
D9/D8 2/	0	N	27.5	52	-.18±.23	- 6.0	18	.01	64	14
03/04	95	E	28.4	54	.16±.32	5.2	18	.05		
C12/C16	35	NE	29.7	57	.37±.34	14.1	19	.001		
F9/F8 2/	48	NE	31.0	60	-.16±.40	- 5.4	21	ns	327	6
C13/C17	15	N	33.0	65	.17±.20	5.5	19	.01		
F5/F10	20	N	35.0	70	-.14±.32	- 3.7	18	ns		

1/ Direction of arrow flying with the wind.

2/ Vectopluviometers adjacent to underlined pairs.

3/ General prevailing wind direction (57°) is against tilt of these gages; with tilt of all others.

watershed F, where wind prevailed from the southeast, possibly due to eddy currents around the steep (60-70%) upper slopes of the watershed. All of the data from the five vectopluviometers were combined to get the average wind direction for the experimental area (heavy broken arrow in fig. 5), which also shows wind out of the southwest (arrow flying with the wind points 57°).

Inclination of rainfall (table 1) at each of the vectopluviometer sites was determined by equation 2. Mean inclination was 20° at the C7/C6 site, where an average wind speed during rainfall of 4.4 mph was recorded by the wind gage. Since the inclination of rainfall is a relative measure of wind speed, it is assumed that on the average wind at 4.4 mph will drive the rain at an angle of about 20° from the vertical. Furthermore, since the mean inclinations at the other four sites with vectopluviometers ranged between 20° and 6°, it seems safe to conclude that wind speed was no greater, and at most sites less, than about 4.4 mph.

DISTRIBUTION OF PRECIPITATION

Areal distribution of precipitation on the Three Bar study area is illustrated in figure 7. Precipitation decreases fairly uniformly downslope from southwest to northeast, which is also the direction of prevailing wind. The isohyetal lines were visually fitted using all of the data collected during the 3-year study. The lines were then uniformly adjusted to represent mean annual precipitation based on nine original gages that were in service from 1957 to 1974. The precipitation gradient averaged 5 inches per 1,000 feet of elevation in the direction of wind flow, which is also roughly at right angle to the Mazatzal ridge and the general contour of the lee side of the mountain front (fig. 8). In the lower portion of the study area the isohyetes did not necessarily parallel the local contour lines, an indication that local relief was not the dominant factor in the distribution of rain over the area.

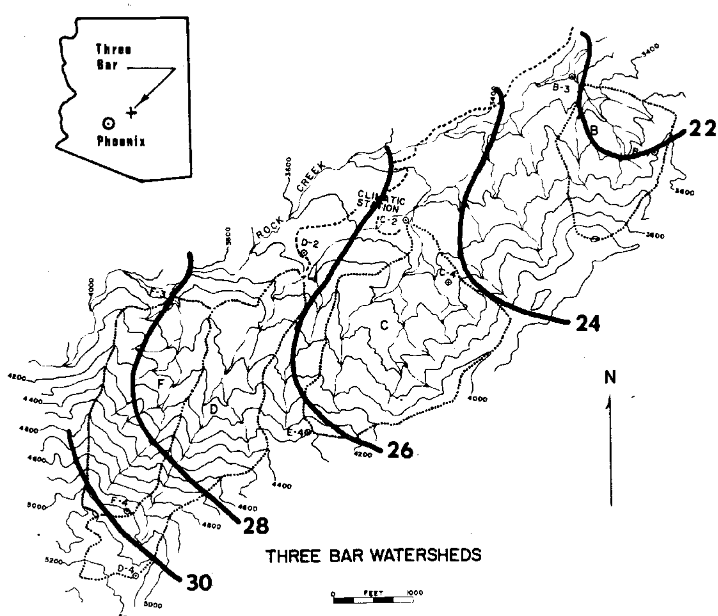

Figure 7. Areal distribution by isohyetal analysis adjusted to mean annual precipitation in inches for 18-year period (1957-1974).

The major physical feature in the surrounding area that might be expected to exert a dominant influence on precipitation is the Mazatzal Divide 1.5 miles to the southwest (fig. 8). Dominated by Four Peaks in this area, the main ridge bears northwest-southeast and is 1,000 or more feet higher than the upper edge of the study area. The prevailing southwest winds blow roughly at right angles across the divide and down over the watersheds. Presumably, orographic uplift of moist air increases precipitation on the windward approach. Then, as the air flows over and down the lee side of the mountain, precipitation rapidly decreases until the terrain levels off. Although local topography clearly modifies wind patterns, and to some extent the local distribution of rain as shown by the tilted gages and vectopluviometers, the general distribution of rain over the study area appears to be controlled largely by the Mazatzal Divide and the leeward flank of the mountains.

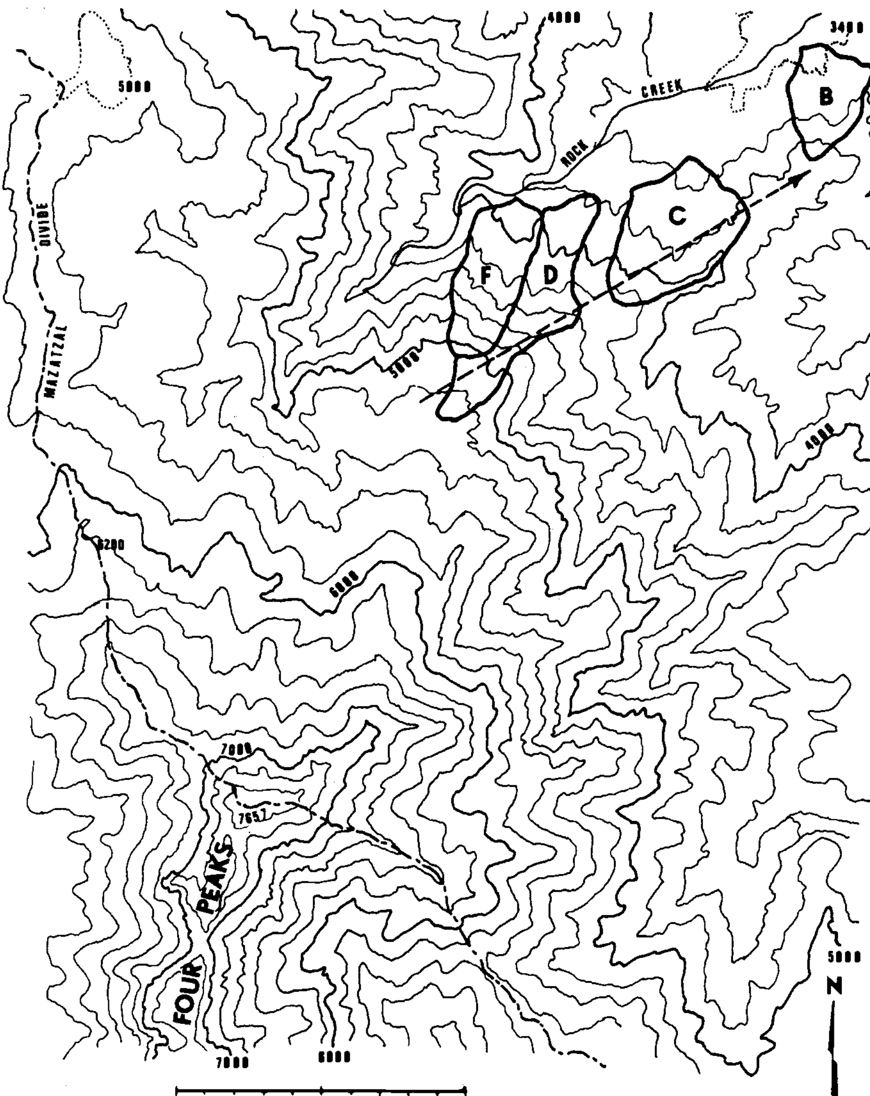

Figure 8. Three Bar watershed in relation to Mazatzal Divide and Four Peaks. Broken arrow shows direction of prevailing wind during rainfall.

How representative of surrounding areas is the distribution pattern defined on this small study area? By extending the 5 inches per 1,000 feet gradient 3.5 miles downslope from watershed B, 16 inches of precipitation is indicated where Tonto Creek enters Roosevelt Lake at 2,200 feet elevation (fig. 1). This amount coincides precisely with the 16-inch isohyete shown for this site on the U. S. Weather Bureau isohyetal map (WR-1210-A) of normal annual precipitation for Arizona (1931-1960). The 16 inches is also in line with long-term means of two nearby gaging stations, Roosevelt and the Reno Ranger Station in Tonto Basin (Sellers and Hill 1974). Precipitation at Roosevelt (2,205 feet) 9 miles to the southwest averages 14.15 inches and at Reno Ranger Station (2,420 feet) 8 miles up Tonto Creek the average is 16.75 inches. This close agreement between extrapolated and measured precipitation indicates a relatively constant precipitation gradient from upper watershed D on the study area to Roosevelt Lake, even though the terrain slopes much more gently below (6%) than within the study area (22%).

Upslope, between the study area and the Mazatzal Divide, no precipitation data are available and the accuracy of extrapolated values is less certain. However, it is obvious that precipitation continues to increase with elevation, only the rate of increase can be questioned. If the 5 inches per 1,000 feet gradient is extrapolated upslope from the 30-inch isohyete on watershed D at 5,000 feet elevation (fig. 7), the amount indicated at 6,200 feet on top of the Mazatzal Divide is 36 inches (fig. 8). This is about 6 inches (20%) more than is indicated for this site on the U. S. Weather Bureau isohyetal map (WR-1210-A), which shows a 30-inch isohyete encircling Four Peaks at about 6,000 feet elevation. This map estimate is low because the same amount is known to occur at 5,000 feet on the study area, where it is apparent from the vegetation that precipitation is not as great as higher on the mountain. Chaparral, which dominates the slopes below 5,000 feet at Three Bar, changes to oak-woodland and ponderosa pine between 5,000 and 6,000 feet. Above 6,000 feet, quaking aspen thrives in cove sites along the northeast exposure of Four Peaks, suggesting that precipitation is greater there than lower on the study area.

Possibly, precipitation does not continue to increase at 5 inches per 1,000 feet all the way to the crest of Four Peaks (7,657 feet), or perhaps even to the top of the divide which varies from 5,800 to 6,500 feet in this area. However, it is certain that precipitation above 6,000 feet exceeds 30 inches; quite probably it is 35 inches or more.

The question logically arises: what is the precipitation like on the windward (southwest) side of the Mazatzal Divide? It is generally believed that less rain falls on leeward than on windward exposures at comparable elevations. This phenomenon is known as the rain shadow effect. Since no rain gages are available on the windward side, vegetation provides the only means of comparison. Casual observations by the author have not disclosed anything about the vegetation on the windward side to indicate that it gets more rain. Actually, the opposite appears to be true; near the top of the divide, the lee side appears to be the wettest. There are two possible explanations. First, the lee side near the top of the divide may be a dump zone for rain and snow that are diverted by strong winds blowing across the summit and dropped as the wind slows on the lee side. This effect should not carry far down the lee side. Second, and probably the most important, the lee side is a northeast exposure, and as such is much cooler, especially during the winter months when the sun angle is low. Precipitation could actually be less on this cool exposure and yet appear wetter than on the warmer southwest side. Thus the rain shadow effect, if it exists, is probably masked by the local climates on these slopes.

SUMMARY AND CONCLUSIONS

The general distribution of precipitation over the Three Bar experimental watersheds is controlled largely by the presence to windward of the Mazatzal Mountains, over 6,000 feet high. Local topography appears to have only minor, localized effects on rain distribution. Prevailing winds blow across the Mazatzal Divide and flow down over the easterly slopes, crossing the watersheds from the southwest to northeast. The terrain is rugged, but the average slope is not particularly steep in the direction of prevailing wind, except on the upper watersheds. From the Mazatzal Divide at 6,200 feet, average slope is 16 percent down to the watersheds, 20 percent across the watersheds, and 6 percent between the watersheds and Tonto Creek at Roosevelt Lake. The precipitation gradient is essentially constant at 5 inches per 1,000 feet of elevation from Tonto Creek to the upper watersheds. While the gradient could not be verified between the watersheds and the divide, the 36 inches of precipitation indicated by extrapolation to the divide appears consistent with the vegetation growing above 6,000 feet. The results of this study suggest that precipitation in the Mazatzal Mountains near Four Peaks may be underestimated by 5 inches or more on the Weather Bureau's isohyetal map of Arizona.

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