RAINFALL VARIABILITY RELATIONS ON SMALL AREAS

F. A. HUFF AND W. L. SHIPP
Illinois State Water Survey

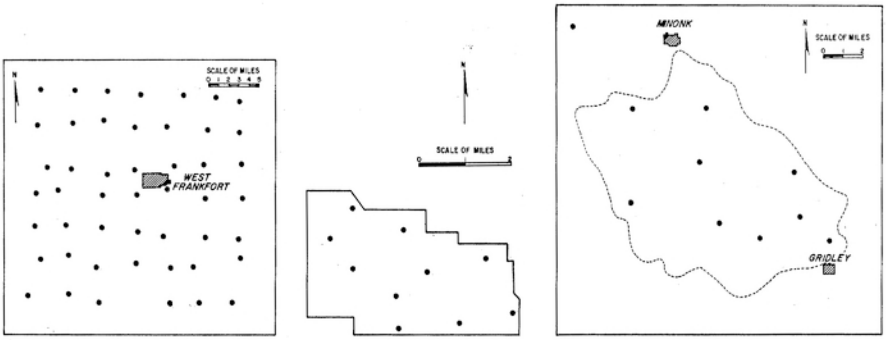
ABSTRACT. — Data from three dense raingage networks operated on areas of 10, 100, and 550 square miles for periods of 7 to 11 years in Illinois were used to determine (1) the time and space variability of storm, monthly, and seasonal precipitation and (2) the relationship of precipitation relative variability to areal mean precipitation, maximum network precipitation, storm duration, precipitation type, synoptic weather type, and season. With storm rainfall, the strongest individual correlation was between relative variability (V) and mean precipitation (P). Seasonally, only small differences were found in the degree of correlation between V and P. V increased with increasing area and was substantially greater with unstable precipitation than with the steady types. Grouped according to synoptic weather type, the highest V was obtained with air mass storms and the lowest with low center passages and warm fronts. The relative variability of monthly precipitation maximized and minimized in different months of the year between networks, apparently reflecting climatic differences in the precipitation from central to southern Illinois. In general, the relative variability was lowest in winter and highest in the warm-season months, and months with below-normal precipitation tended to have higher relative variability than above-normal months. Results from this study should provide background information valuable in hydrometeorological applications and in verification programs for weather modification experiments.

The existence of relatively large spatial and temporal variability in precipitation, particularly in thunderstorms and rainshowers, is generally recognized among meteorologists and hydrologists. However, knowledge to define this variability in quantitative terms has been inadequate, especially with respect to small areas and various types of storm conditions. In hydrometeorology, such knowledge is pertinent to establishing watershed raingaging facilities and in interpreting rainfall-runoff relationships. In weather modification studies, precipitation variability must be considered in both the planning and verification of field experiments. Failure to do so may lead to poorly designed sampling programs and invalid interpretation or experimental results.

In Illinois, data were available from several concentrated raingage networks operating for periods ranging from 7 to 11 years and encompassing areas of 10, 100, and 550 square miles. These data have been used to determine quantitatively relative variability on a storm, monthly, and seasonal basis and to show the relationship of precipitation variability to areal mean precipitation, maximum network precipitation, storm duration, precipitation type, synoptic weather type, and season.

DATA AND ANALYTICAL PROCEDURES

The three sampling networks are shown in Figure 1. The Little Egypt Network in southern Illinois has been in operation for 9 years and consists



LITTLE EGYPT, 550 SQUARE MILES BONEYARD, 10 SQUARE MILES PANTHER CREEK, 100 SQUARE MILES

FIGURE 1. Raingage Networks Used in Study

of 49 raingages in 550 square miles. The 9-year sample (1958-1966) provided 964 storms in which the areal mean rainfall equalled or exceeded 0.01 inch, the basic requirement for inclusion in the variability study. The Panther Creek Network of 9 raingages on 100 square miles in north-central Illinois contributed 724 storms to the study during the 1954-1960 period. During 1954-1964, the Boneyard urban network of 10 raingages in 10 square miles, located at Champaign-Urbana in east-central Illinois, provided 1066 storms. All networks are located in relatively flat terrain which is characteristic of the major midwestern agricultural regions. For the few storm data that were missing because of occasional mechanical problems at some of the gages, amounts were estimated through the use of isohyetal maps.

The spatial relative variability was obtained by the simple method presented by Conrad and Pollak (1950), in which it is defined by:

$$V = 100(AD/M) \qquad (1)$$

where V is the relative variability in percent, M is the mean of the sample, and AD is the average deviation from the mean.

After determination of the mean rainfall, average precipitation duration, and average deviation in each storm, Equation (1) was used to determine the relative variability. For storms that did not have measurable rainfall at some gages in the network, a second calculation of relative variability was made after eliminating the zero or trace observations. This provided a more useful variability measure for some applications. At the same time, the number and percentage of gages (area) without precipitation were tabulated as additional statistics.

In the storm studies, correlation analyses were used to determine the degree of relationship between storm relative variability (V) and areal mean precipitation (P), maximum network precipitation (P_m), and storm duration (D), when the storms were grouped by synoptic weather type, precipitation type, and season. Simple and multiple correlation coefficients were determined with the data expressed in both linear and logarithmic terms. From the correlation analyses, decisions were made on the regression analyses to be performed with respect to data transformation and independent variables.

In the monthly and seasonal calculations of spatial variability in total precipitation (P_t), the relative variability was calculated with Equation (1). Relations were developed between V and P_t and comparison made of the magnitude of V between seasons and between wet and dry periods. Probability estimates of monthly variability were also developed.

STORM RELATIONS

In the study of individual storms, correlation analyses produced higher coefficients with logarithmic transformations than with the linear variables, as indicated by graphical plots of the data in preliminary studies. The differences are illustrated in Table 1 in which linear and logarithmic computations of correlation coefficients (r) and coefficients of determination (r^2) are shown for V, P, and D in summer storms on the Little Egypt Network.

Table 1 is typical of the results obtained with the data grouped according to season, precipitation type, and synoptic weather type. As indicated in Table 1, only a small improvement in the relationships was found when V was related to both P and D as opposed to P alone. This is due to the strong correlation between P and D; as mean rainfall increases the storm duration also tends to increase. Consequently, it was decided to develop regression equations relating the logarithms of V and P.

Table 1.—Linear and Logarithmic Correlations Between V, P, and D in Summer Storms on Little Egypt.

Transformation	r			r^2(%)		
	V-P	V-D	V-P, D	V-P	V-D	V-P, D
Linear	−0.47	−0.51	0.55	22	26	30
Logarithmic	−0.75	−0.70	0.79	56	49	62

Regression equations were developed with the data grouped according to season, precipitation type, and synoptic weather type. Further analyses indicated that the seasonal grouping primarily reflected the frequency distribution of precipitation types in the four seasons. Therefore, for evaluation purposes the seasonal grouping was eliminated and the precipitation type classification was selected and is summarized in Table 2.

Table 2.—Precipitation Type Comparisons of Relative Variability.

All Gages

Precipitation Type	Number of Cases	Average Relative Variability (%) for Given Mean Rainfall (in.)					
		0.05	0.10	0.25	0.50	1.00	2.00
Little Egypt (550 Square Miles)							
TRW	436	117	85	56	41	30	23
RW	227	83	61	41	30	23	17
R	219	54	40	27	20	15	11
S	82	45	33	22	16	..	..
Panther Creek (100 Square Miles)							
TRW	146	72	55	38	29	22	17
RW	317	67	50	35	27	21	16
R	170	52	39	27	20	15	11
S	91	52	39	27	20	..	..

Boneyard (10 Square Miles)							
TRW	442	63	44	28	20	14	10
RW	235	51	36	23	16	11	8
R	239	37	26	17	12	8	6
S	151	31	24	17	14	..	..
Only Gages with Measurable Amounts							
Little Egypt							
TRW		89	69	49	38	30	23
RW		71	54	38	29	22	17
R		44	35	25	19	14	11
S		35	27	19	15	..	..
Panther Creek							
TRW		52	42	32	27	21	17
RW		47	38	29	24	20	16
R		40	31	23	18	14	11
S		40	31	23	18	..	..
Boneyard							
TRW		49	36	24	18	13	10
RW		40	29	20	15	11	8
R		29	22	15	11	8	6
S		29	23	17	13	..	..

Precipitation Type Grouping

In Table 2, V is shown for selected values of mean rainfall on each of the three sampling networks based upon all sampling points and upon only those raingages with measurable precipitation. If more than one precipitation type occurred in a storm, it was assigned to the predominating type with respect to the total storm precipitation. Precipitation was classified as thunderstorms (TRW), rainshowers (RW), steady rain (R), and snow (S). Other types were too few to be included in the study.

Before discussing Table 2 further, it should be emphasized that snow measurements are subject to relatively large sampling errors, especially in strong winds and with low-density snow. Consequently, the values of V are probably larger than the true values in nature, and the snow relations should be considered only rough approximations for comparison purposes.

In general, Table 2 shows the expected trends for the relative variability to decrease with decreasing area and increasing mean rainfall, and to be substantially greater with the unstable types of precipitation (TRW, RW) than with the steady types (R, S). For the smaller mean rainfalls, which are more likely to result from storms of smaller areal extent and shorter duration than the heavy storms, a significant decrease in variability was found when only gages with measurable precipitation were used. However, the sampling area decreases in these cases and this contributes also to the decreasing trend in V.

The decreasing relative variability with increasing mean rainfall results from general trends for heavier storms to last longer and have greater areal extent. The increasing relative variability with increasing area results from the greater range of rainfall values which occur, on the average, as the size of the sampling area increases. The primary importance of Table 2 with respect to these two relationships of relative variability is the establishment of quantitative measures of the V-differences with increasing area and volume of precipitation.

Another quantitative measure of equal or more interest in Table 2 is the V-differences among precipitation types. On the Little Egypt Network in southern Illinois, the ratios of the unstable rainfall types, TRW and RW, to the stable type, steady rain, were approximately 2.1 and 1.5, respectively, for all gages. On Panther Creek, these ratios were 1.4 and 1.3, respectively, and on the Boneyard Network they averaged 1.7 and 1.4. It is believed that the primary cause of the network ratio differences proceeding northward is the greater proportion of storm rainfall associated with air mass showers of relatively small areal extent and steep spatial gradients in the southern part of the state (Huff, 1966).

Snow values have been omitted for mean precipitation greater than 0.50 inch in Table 2 because of the small number of cases. The same curve fit both R and S on Panther Creek, whereas the relative variability of snow was somewhat less than steady rain on the other two networks. Considering areal size, the higher values of V for snow on Panther Creek compared with Little Egypt is unexpected. This apparent inconsistency is believed to arise from the occurrence of lower-density snow with stronger average winds on Panther Creek. These conditions resulted in greater drifting and less reliable sampling than on the Little Egypt network.

Synoptic Type Grouping

Table 3 summarizes the results of determining the V-P relation for all gage observations after grouping of the data according to synoptic weather type. This was done to obtain a quantitative measure of the effect of major storm types on V. Six basic types of storms were used, as shown in Table 3. Low centers and occluded fronts were combined, because the few cases of occluded fronts appeared similar in V characteristics to the low center storms. The number of cases in each category is included as an indication of the sampling adequacy.

Unfortunately, the regression curves from which Table 3 was constructed did not produce parallel curves, so that a simple statement of the relative effects of each type cannot be made. Combining all values of P, air mass storms showed the greatest relative variability on all three networks, although static fronts had larger values for very light rains on Little Egypt and there were several cross-overs at the heavier values of P on Panther Creek. The Panther Creek sample was somewhat smaller than those for the other two networks, especially for the heavier rainfalls, so that the cross-overs may be more sampling vagaries than real properties.

Low centers and warm fronts showed the lowest relative variabilities among the storm types in Table 3. These systems are more likely to be associated with widespread precipitation of relatively long duration over a given sampling area than air mass, cold frontal, and squall-line storms which show considerably higher variabilities. Stationary frontal storms, which show high variabilities especially at the heavier rainfall levels, are often of long duration but are frequently associated with intense thunderstorms and rainshowers with steep gradients which tend to produce high relative variability on a given sample area.

MONTHLY, SEASONAL, AND ANNUAL VARIABILITY

For some purposes, long-term differences in relative variability on a given area over periods of a month, season, or year are of more interest than storm variability. One example is the establishment of sampling requirements for long-term weather modification experiments. Monthly and 3-monthly values of average relative variability on the Boneyard Network of 10 square miles and Little Egypt Network of 550 square miles are shown in Table 4.

The intermonthly and interseasonal differences are considerably greater in the southern Illinois network than in the east-central Illinois network. Also, a pronounced maxi-

TABLE 3.—Synoptic Storm Type Comparisons of Relative Variability.

All Gages

Storm Type	Number of Cases	Average Relative Variability (%) for Given Mean Rainfall (in.)					
		0.05	0.10	0.25	0.50	1.00	2.00
Little Egypt							
Air Mass	127	97	81	64	54	45	38
Cold Front	235	83	71	49	34	28	21
Warm Front	43	62	52	42	37	30	25
Static Front	182	110	82	54	40	30	22
Low Center—Occluded Front	302	62	45	29	23	15	11
Squall Line	77	130	88	52	34	23	15
Panther Creek							
Air Mass	118	84	57	40	30	23	17
Cold Front	184	56	44	32	25	20	16
Warm Front	49	54	40	27	20	15	11
Static Front	141	64	52	39	31	25	20
Low Center—Occluded Front	184	46	36	27	22	17	14
Squall Line	48	79	57	38	27	20	13
Boneyard							
Air Mass	118	74	53	34	25	18	13
Cold Front	267	41	32	24	19	15	12
Warm Front	60	53	36	21	14	9	6
Static Front	169	55	40	26	19	14	10
Low Center—Occluded Front	362	36	26	18	13	10	8
Squall Line	91	57	38	23	15	10	7

TABLE 4.—Monthly and Seasonal Comparisons of Relative Variability.

Network	Monthly Averages											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Little Egypt	9	10	9	11	15	18	20	19	23	36	11	8
Boneyard	9	8	7	7	8	10	10	12	12	8	8	7

Network	3-Month Averages											
	Jan.-Mar.	Feb.-Apr.	Mar.-May	Apr.-June	May-July	June-Aug.	July-Sept.	Aug.-Oct.	Sept.-Nov.	Oct.-Dec.	Nov.-Jan.	Dec.-Feb.
Little Egypt.	10	10	11	15	17	19	20	26	23	18	10	9
Boneyard..	8	7	7	8	9	10	11	10	10	7	8	8

mum from late summer to early fall is indicated in southern Illinois. This maximum reflects a trend for unstable precipitation from showers of small areal extent to dominate the southern Illinois precipitation climate during these months. The Little Egypt Network, as indicated earlier, receives a greater portion of its total precipitation from the highly variable air mass storms than does the Boneyard Network. Effects of these storms, which occur most frequently from spring to fall, are reflected in the greater range of monthly values on Little Egypt.

An examination of months with above and below normal precipitation on the two networks showed the "dry" months with an average V of 19 percent, compared with a "wet" month average of 12 percent on Little Egypt. Similarly, the below normal months averaged 10 percent compared with 7 percent in the above normal months on Boneyard. This reflects the effects of fewer, lighter, and less extensive storms in the dry months. A probability distribution of monthly relative variability, grouped by season, is presented for the two networks in Table 5 to provide a more detailed description of the monthly distribution.

A comparison was made of the annual relative variability on the two networks during the 9-year period, 1958-1966. V averaged 4.4 percent on Little Egypt with a range of 3 to 6 percent, compared with a mean of 3.6 percent and a range of 2 to 6 percent on Boneyard. When 2-year to 5-year moving averages were computed, relative variabilities of 2 to 3 percent were obtained on the two networks. Thus, when precipitation is averaged over several years, the effect of spatial variability becomes minor in regions of approximately homogeneous precipitation climate, and the small values probably reflect sampling errors to a larger extent than true precipitation differences. These findings are useful in several applications, such as the establishment of sampling periods for the determination of precipitation normals and in the planning of precipitation modification experiments.

CONCLUSIONS

The spatial relative variability of storm precipitation was found to be related exponentially to mean precipitation. The relation was not significantly improved by adding other variables, such as storm duration and maximum storm precipitation. The relative variability tends

TABLE 5.—Probability Distribution of Monthly Relative Variability Grouped by Season.

	Relative Variability (Percent)							
	Little Egypt				Boneyard			
Probability (Percent)	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
5	18	31	36	109	17	17	27	16
10	16	24	29	53	14	14	21	16
20	13	14	23	31	12	10	14	13
30	10	12	22	28	9	8	11	12
40	9	10	20	24	9	7	10	11
50	9	9	18	16	8	7	10	10
60	8	8	16	12	7	6	8	8
70	7	8	15	10	6	6	7	7
80	6	7	14	9	6	5	6	5
90	5	7	12	6	5	4	6	4
95	4	6	11	6	3	3	6	4

to increase with increasing area and to be substantially greater with unstable types of precipitation (RW, TRW) than with steady types (R, S). Grouped by synoptic weather type, the highest relative variability, in general, was obtained with air mass storms and the lowest with low center passages and warm fronts.

The relative variability of monthly precipitation was found to maximize and minimize in different months of the year between sampling networks, apparently reflecting climatic differences in precipitation from central to southern Illinois. In general, the relative variability was lowest in winter and highest in the warm-season months, and months with below-normal precipitation tended to have higher variability than above-normal months.

Analyses of annual relative variability showed that spatial variability becomes minor in regions of approximately homogeneous precipitation climate when precipitation is averaged over a period of two to five years.

LITERATURE CITED

CONRAD, V. and L. W. POLLAK. 1950. Methods in Climatology. Harvard University Press, Cambridge, Mass., pp. 54-55.

HUFF, F. A. 1966. The Effect of Natural Rainfall Variability in Verification of Rain Modification Experiments. Water Resources Research, Vol. 2, No. 4, pp. 791-801.

Manuscript received September 7, 1967.