Rainfall Variability

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Introduction

Monthly and annual rainfall are not only not the same in all places, but vary from year to year in a single location. Where the annual variation is not great, as in Indiana, biotic forms and human culture, being somewhat flexible, are able to compensate for most of the variations. Where the variation is great, or the local environment is being worked close to theoretical limits, extensive compensatory mechanisms must be set up, or each deviation of the rainfall from the optimum value produces great biotic and economic hardship. Prior to about 1940, Indiana had land to spare, so that rainfall variability was of academic interest only to all except a few specialized engineers. Today, and probably for all of the foreseeable future, with increasing production costs, and continuing world-wide food shortages, demand for Indiana farm products is increasing, and at the same time present supplies of agricultural and municipal water are being crowded. In consequence, for the average resident of Indiana, rainfall variability has acquired, or will shortly acquire, a definite personal importance.

Rainfall variability is not only not shown, but is effectively concealed, by the standard climatic charts, which customarily show mean monthly temperatures and precipitation, usually computed for "the life of the record," which, at many stations, is more than half a century. Despite this omission, these charts are extremely useful indicators of average conditions. Charts for four stations—Yuma, Arizona; Salt Lake City, Utah; Bloomington, Indiana; and New York City, N. Y., comprise figure 1. Quite obviously, agriculture in Yuma will be productive only of tumbleweeds and guayule unless irrigation is used. By diversion of almost the entire flow of the Colorado River, the once-arid Salton Sink, west of Yuma and climatically similar, has become the fertile and productive Imperial Valley. Similar procedures, but less extensive, have made the Salt Lake area highly productive.

Reference to the Bloomington chart shows that irrigation is not necessary, for most crops, in a statistically normal year, for not only is rainfall plentiful, but it is fairly well distributed through the year. A slight increase in the production of some crops might be possible if a portion of the normally high rainfall of March and April were stored for use during the comparatively dry month of July. Whether such storage is economically desirable under present conditions is questionable.

The mean rainfall shown in these charts is the ordinary average, computed by adding a number of rainfall values, and then dividing the sum by the number of values added. As is well known to meteorologists

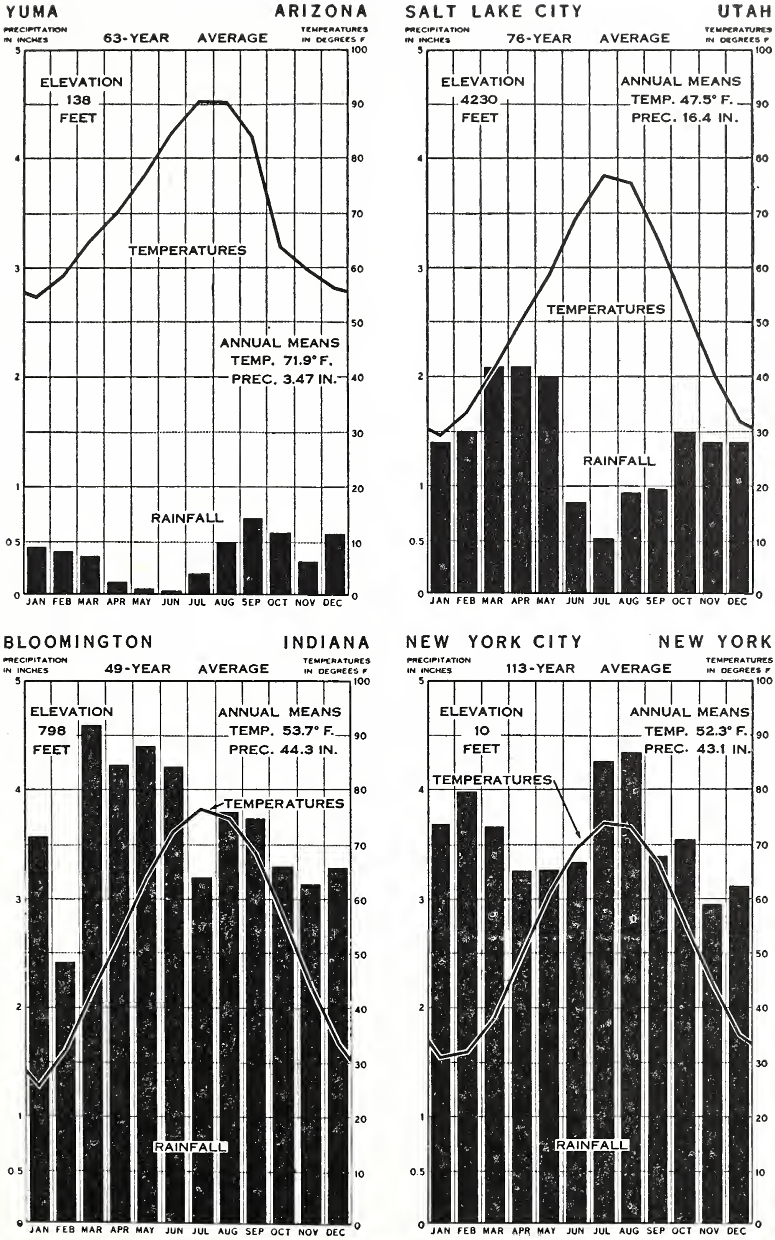

Fig. 1. Climatic charts for Yuma, Arizona; Salt Lake City, Utah; Bloomington, Indiana; and New York City, N. Y.

and climatologists, the mean value, which is also known as the normal, or average, is the value least commonly recorded at many stations.

Rainfall Variability

Rainfall variability, which is not shown on conventional climatic charts, may be of greater biotic and cultural importance than the mean value of the rainfall. If the rainfall in a given area is consistent enough so that each annual planting at least "returns its seed," then a relatively simple cultural organization is possible. Such has been the case in most parts of the "corn belt" of the United States. If, however, rainfall is so variable that a crop is successful only one year in four or five, then a sedentary population must adopt a much more complicated culture, able to store either seed or water, or both, to insure survival through several dry years. In ancient times, the inhabitants of the dry southwest stored seed for long periods; today, water is stored in a series of complicated and expensive reservoirs.

An alternative to the storage of seed or water, or both, is migration over a large area. This is fairly successful where rainfall is erratically distributed, and was used for many generations by the Pima-Papago Indian groups in Arizona and Sonora. Planting of fast-maturing crops was done immediately after a rain, in an area where soil moisture was retained. This "temporale" agriculture, still used in parts of Sonora, is rather surprisingly productive, but is suitable only for areas of low population density.

A "horrible example" of rainfall variability is shown by the Yuma, Arizona, rainfall record, comprising figure 2. Here, the rainfall in some

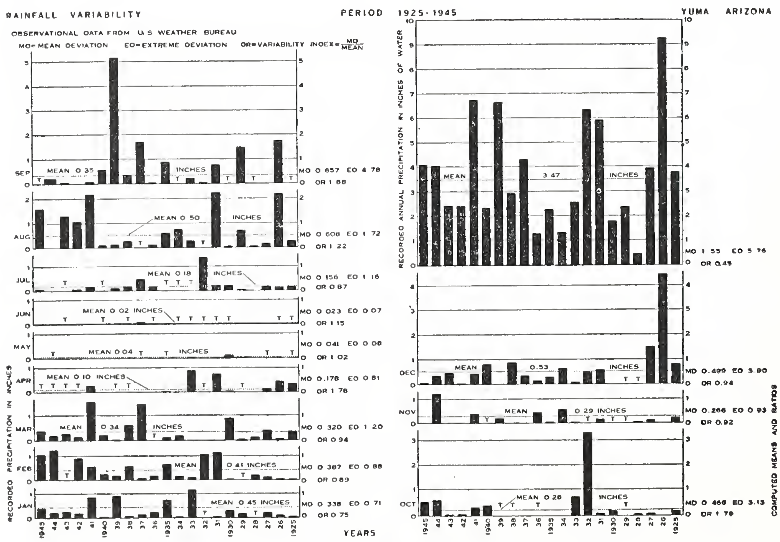

Fig. 2. Monthly and annual rainfall at Yuma, Arizona, for the period 1925-1945 inclusive. Rainfall variability here is extreme.

months (occasionally all from a single "cloudburst") exceeds that for some years. In some years here, without irrigation, even a cactus crop would fail: in others, the cacti would be washed away. Variability at other stations (figure 1) is markedly less[1] the regularity of the rainfall, *in general*, becoming greater as the annual total increases.

Measures of Variability

Rainfall variability may be measured in a variety of ways, most of which have definite and specific uses; none of which fit all needs. Simplest method is to record the actual rainfall at a station, and then to determine the deviation of the recorded value from the cumulated mean for that station. This method is followed by the U. S. Weather Bureau in the preparation of the monthly and annual *Climatological Data* sheets for the various sections.

Although the actual deviations, or the mean of these deviations ("Mean deviation") are of considerable local value, their general value and significance are slight, for an annual deviation of four inches is likely to be disastrous in Yuma, Arizona, for example, but of little significance in Bloomington, Indiana. Several areal studies suggest that mean rainfall deviations are more uniform than mean rainfalls.

In addition, most life forms, upon which our culture and existence are ultimately dependent, can tolerate a considerable variation in water supply, but this variation is commonly a factor of the optimum for that form. Its value depends upon the specific crop, but is commonly from 1.1 to 1.5.

In consequence, the most useful simple measure of rainfall variability is the variability index, computed by dividing the mean deviation in rainfall at a given locality by the mean rainfall for the same locality.

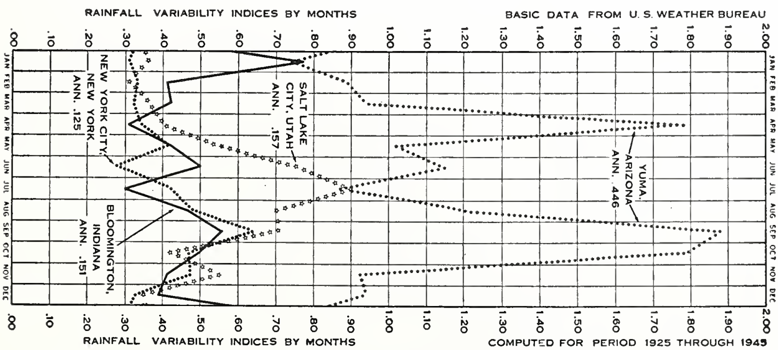

Fig. 3. Rainfall variability indices for Yuma, Arizona; Salt Lake City, Utah; Bloomington, Indiana; and New York City, N. Y.

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[1] Variability at Salt Lake City is discussed in Ives, R. L., Inter-relations of Terrain, Weather, and Climate in the Southern Salt Lake Desert, forthcoming; and that for Boomington, Indiana, is described in a paper being prepared by M. W. Wise, of Indiana University.

Variability indices, computed on this basis, for the four stations graphed in figure 1, are shown in figure 3. With present records and rainfall regimes, this index seems most suitable for extensive studies of rainfall variability.

Where agricultural production depends not only upon immediate rainfall, but also upon some "delayed" factor, such as filling of a reservoir, recharge of an aquifer, melting of snow, or saturation of a subsoil component, simple month-by-month variability indices may not be adequate, and some cumulative system will be found useful. Simplest of these systems is computation of the mean deviation of the rainfall cumulative from a given date, such as Jan. 1 of the year concerned. Many actual problems are even more complex, calling for use of an attrition formula, having the general form K log B, in which both B and K are compound factors, determined from study of local conditions. Comparison of the simple variability index, computed on a monthly basis, with an index computed from values cumulated since Jan. 1, for Bloomington, Indiana, for the period 1925-1945, is included in figure 4. It will be noted that where the rainfall is, or can be, cumulated, by any means, until late spring, the variations in the cumulated amount, and hence in the amount of water available during the growing season, are greatly lessened.

Forecasting Possibilities

In a very general way, it can be stated that in two thirds of the years in any given long sequence (20 years or more), the rainfall will be within the limits of the mean plus the mean deviation, and the mean minus the mean deviation. This approximation is valid for most locations in North America, its dependability declining as the rainfall variability index increases. Theoretically, by use of the Pearsonian *coeffcient of variability*[3], rainfall variations could be evaluated on an actuarial basis, making possible more effective crop insurance at lower cost. Such a coefficient of variability, computed for Bloomington, Indiana, for the period 1925-1945, is shown in figure 4. It will be noted that this is slightly greater than the variability index, previously computed. The difference is caused by the squaring of the deviations, a procedure which gives greater emphasis to larger deviations.

Where the "population" is stable, and the distribution curve is only moderately skewed, the probability of any amount of variability can be determined to any accuracy desired. Most unfortunately, we have no assurance that the "population" (in this case climate) is stable, and much reason to suspect that it is subject to a number of cyclical variations, complicated by fluctuations that now appear to be "pure random." Some progress has been made in correlating climatic fluctuations with sunspot cycles, and integral multiples of the sunspot cycle

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[3] Derivation of these indices is outlined in "Formulae" at the end of this paper.

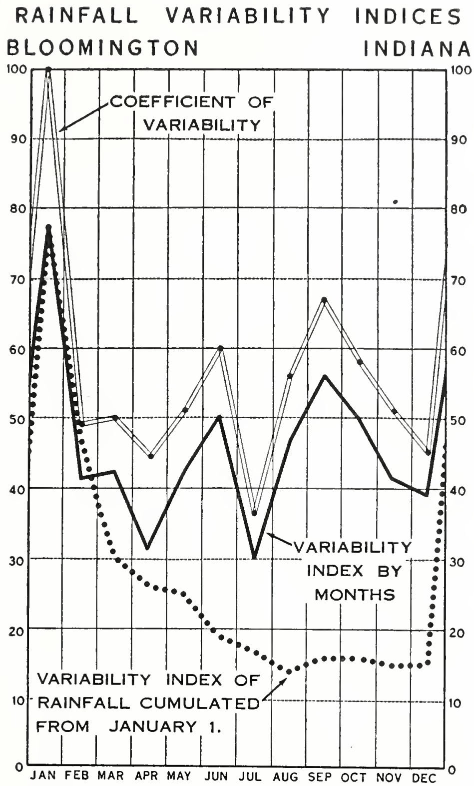

Fig. 4. Comparison of various rainfall variability indices.

(roughly 11 years). Other workers have demonstrated that rainfall in some areas (and only in some areas) bears a definite relation to the solar radiation incident some time previously, not always in the area under consideration. After all of the known and suspected cyclical variations are accounted for, there are still "gremlins" in most rainfall distribution curves. These must be accounted for before rigorous mathematical procedures can be applied to rainfall forecasting.

In addition to the above, most rainfall curves are immoderately skewed, with the absolute maximum value being many times the mean. Not only is the rainfall inconstant, but the amount of skew is not fixed, so that ordinary statistical methods cannot be applied to the problem with any confidence.

Because of the shifting of mean values, use of the standard deviation, and of the Pearsonian coefficient of variability, is not advisable. In contrast, with a slowly shifting mean, values determined by computation of the variability index, in which the deviations are not squared, remain valid for a considerable period, and the errors introduced by slow shifts of the mean cancel out, in time, particularly if the shiftings are of a cyclical nature.

Scatter of the annual values, for the period 1900-1948, for Bloomington, Indiana, is compared with variously computed means in figure

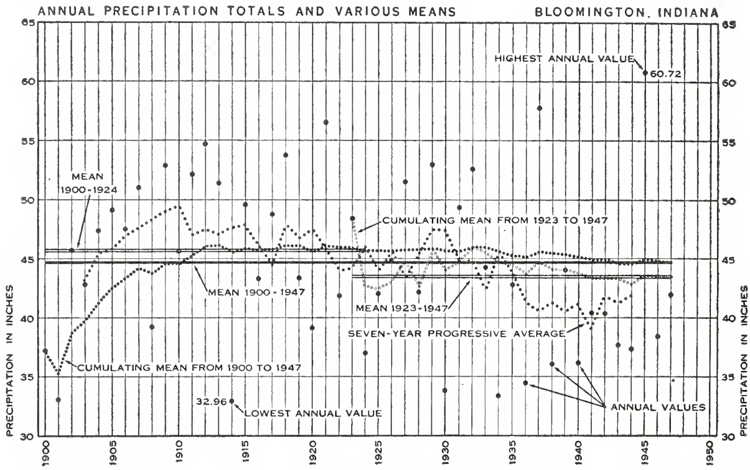

Fig. 5. Rainfall values for Bloomington, Indiana, as averaged by various statistical methods.

5. Much climatic computation is based on the cumulating mean, beginning when records were started, and continuing to the year under consideration. Note here that the mean rainfall for the first 25 years of the record is not the same as that for the last 25 years; and that neither is the same as that for the total record.

The progressive average shown in figure 5 is one of several methods used to detect and predict trends. Here it shows a slight erratic upward trend in local rainfall, following a short period of slightly decreased mean precipitation.

The problem of forecasting, as well as that of formulating general working rules, is complicated by the difficulty of applying a general rule to a specific case. For example, the generalization "rainfall variability increases as the total amount decreases" is quite satisfactory when annual totals of rainfall are considered, but fails miserably when monthly totals are concerned. At the four stations considered in figures 1 and 3, in only one case (Salt Lake City) does the month of minimum rainfall also have the maximum variability; and in no case does the maximum monthly rainfall coincide with the month of minimum variablity. Monthly values of rainfall are plotted against monthly variability indices, for the four stations, in the figure 6.

It has been suggested that, whereas a stable average of annual rainfall totals may be attained at most stations in a period of 35 years

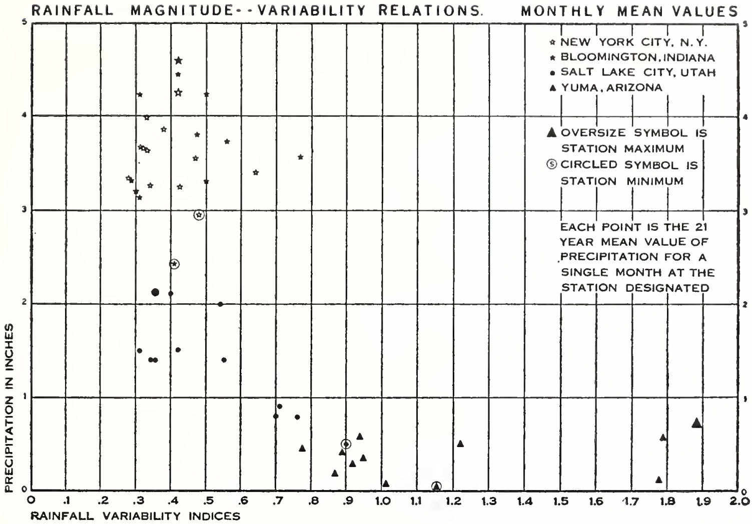

Fig. 6. Rainfall magnitude compared to rainfall variability for the period 1925-1945 for Yuma, Arizona; Salt Lake City, Utah; Bloomington, Indiana; and New York City, N. Y.

or so, the monthly averages will not stabilize until a much longer period has elapsed. Correctness of this suggestion, which is not unreasonable, is hinted at by perusal of the records for London, England. A rigorous check, for a period of about 350 years, for a station where the physical environment is constant, is both very desirable, and completely impossible. There is no such station.

As a result of the multifarious unresolved problems related to cyclical and random climatic fluctuations, possible unidirectional trends, in part "inherited from the Pleistocene ice ages; and the short span of human records and observations; it appears that the more rigorous and valuable statistical methods, such as use of the Pearsonian coefficient of variability, cannot be applied with any hope of correctness to rainfall variability problems at the present time; but that the cruder methods, based on the variability index, are very useful, within their acknowledged limitations, today.

Applications of Rainfall Variability Data

Variability of rainfall is all too commonly considered a problem of interest only in areas of irrigation agriculture. In those areas, rainfall variability is certainly a problem, but nearly every Indiana community is directly concerned with the same problem. Municipal water supplies, for domestic and industrial use, are very greatly affected by cumulating rainfall deficiencies of medium duration (such as 24 months). Before water supplies in many Indiana communities can be regarded as satisfactory, additional construction, to compensate for the effects of both immediate and cumulated water supply shortages, will be necessary.

When the rainfall exceeds the mean value for the period under consideration, the water-disposal facilities are affected. This includes municipal street and sewer departments; flood control works; and erosion control agencies. The problem here becomes quite complex, for the municipal facilities are concerned with getting rid of the water rapidly, whereas the flood control works, as well as the erosion control methods, are designed to retard and stabilize runoff.

Both water storage and water-disposal facilities must be designed to function under a wide variety of conditions, both of excess and scanty water; and to function satisfactorily with a minimum of interference with local water tables. In some instances at least, solution of the problem of flow stabilization has created a new problem of mosquito control.

Both rainfall scarcity and rainfall surplus can be largely compensated for by construction of proper dams, reservoirs, and similar structures, and such structures are costly. Such construction is insurance, and there is always the possibility of overinsurance. If either flood or drought protection costs more than the damage likely to be produced by a flood or drought, there is a possibility that it is undesirable, or "overengineered." In very general terms, water control facilities which permit normal operation when the annual rainfall is within the limits of the annual mean plus or minus twice the annual mean deviation are the maximum that are economically justifiable under present conditions in most areas. Rough probability computations indicate that with such protective measures, normal operation will be prevented by rainfall variations only about once in 20 years.

Conclusions

The foregoing consideration of the problem of rainfall variability indicates that Indiana is located in a region where such variability is not great, and where, in addition, rainfall is adequate for the present economy.

Relatively minor water control works will be able to equalize the annual rainfall distribution sufficiently to permit a slight increase in agricultural production, when construction of such works is economically desirable.

Somewhat more extensive water control structures are already necessary to reduce flood damage, and to provide municipal and industrial water. Many of these works are at present inadequate, and rainfall variability must be considered as they are expanded.

Both overexpansion of water control facilities and overscientific methods of determining rainfall variability must be guarded against, because both are costly errors, leading to overinsurance, and, in most cases, inordinately high tax bills.

FORMULAE

Individual values $= X$

Number of values $= N$

(Σ = "the sum of")

$$\text{Arithmetic mean} = \overline{X} = \frac{\Sigma(X)}{N}$$

$$\text{Individual deviations} = x = |X - \overline{X}| = |X - \frac{\Sigma(X)}{N}|$$

$$\text{Mean deviation} = MD = \frac{\Sigma|x|}{N} = \frac{\Sigma|X - \overline{X}|}{N} = \frac{\Sigma|X - \frac{\Sigma(X)}{N}|}{N}$$

$$\text{Variability index} = \frac{MD}{\overline{X}} = \frac{\Sigma|X - \frac{\Sigma(X)}{N}|}{\Sigma(X)}$$

$$\text{Standard deviation} = \sigma = \sqrt{\frac{\Sigma|X - \frac{\Sigma(X)}{N}|^2}{N}}$$

$$\text{Coefficient of variability} = \frac{\sigma}{\overline{X}} = \frac{\sqrt{\frac{\Sigma|X - \frac{\Sigma(X)}{N}|^2}{N}}}{\frac{\Sigma(X)}{N}}$$