OTHER WORKSHOP PAPERS

PLANNING FOR GREATER AGRICULTURAL PRODUCTION WITHIN RAINFALL LIMITS

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The interaction of solar energy and precipitation is perhaps the most vital ingredient of the environment of the biosphere. While man exerts negligible control over either of these natural phenomena, knowledge about these processes permits planning that reduces losses due to crop failure. The geographical location of the Caribbean region just north of the equatorial zone ensures that solar radiation is relatively high throughout the year, and it also determines the uneven distribution of precipitation in the same time period. This paper is concerned with variations in rainfall, as well as the ability to make precise statements of the reliability of specific rainfall data for the purpose of planning more accurately for greater agricultural production.

The islands and other land masses of the Caribbean basin experience three types of rainfall. The east coasts of these areas are exposed to moist, maritime, tropical air masses brought by the north-east trades or north tropical easterlies from the oceanic sub-tropical high pressure cell. These air masses are abundantly supplied with moisture, and when they encounter hills and mountains, the forced ascent of air results in heavy orographic precipitation. This is the dominant type of rainfall. Slopes on the leeward side as well as flat islands do not receive as much rainfall, and because of adiabatic heating of the descending air, the former tend to be drier or even arid, and possess little potential for agricultural activity. Both must therefore depend for their precipitation on the periodic progression of easterly waves with rainy weather, and on convection rainfall from great cumulonimbus masses generated by the convective cells and high specific humidity.

The tropical easterlies with their heavy rainfall do not always dominate the region, and there is a tendency toward dryness in February, March, and April. This is the period of low sun when the influence of the sub-tropical high pressure cell is greatest with its characteristic vertical subsidence and horizontal divergence. The overall effect is that there is a distinct rainy period and a dry season. However, simple knowledge that some years will be wet and others dry, or that one season and some months will be dry, and the other season and other months, wet, is simply not enough. That is the level of information upon which small-scale farmers operate. Agricultural planners and decision-makers require much more technical data than this. They may want to know what is the most suitable planting date, or how to avoid gross overestimation or underestimation of risk for a particular crop or crops for a particular season. There interests may require some guide to the agricultural capabilities of a district, or the best form of land use based on rainfall data. In planning the development of new regions, the suitability of a virgin area for arable cropping over a short time-period may be crucial. Given adequate rainfall records, the agro-meterorologist can provide reasonable answers to these questions.

It does not appear that very efficient use is made of the long records of rainfall which are available in the Caribbean. The relatively dense network of rainfall stations in most of the territories provides a wealth of data which date back to the early days of the sugar plantation system. In other parts of the world, especially in tropical East Africa, the estimation of the reliability of a particular pattern of rainfall by month, within a season, or by year, has proved invaluable for agricultural production purposes. Given the overwhelming need for self-sufficiency in food production in the region, it is proposed herein to present a few relatively simple methods by which rainfall data can be analysed to aid in such a programme. However, because data for the island of St. Kitts - whose economy is based entirely on agriculture - were readily available, the analysis is confined largely to data from that island. Nevertheless, the methods have application to any territory in the region for which there are appropriate data.

Determining the Reliability of Rainfall: Monthly, Annual, Seasonal

Knowledge of the reliability of rainfall is important to the practical agriculturalist for two main reasons. First, the availability of water is often the decisive limiting factor to the growth and productivity of crops in marginal rain areas, and accurate information on such availability becomes necessary for decision-making. Second, even where the average expected rainfall is known, one still needs to know the confidence limits within which that rainfall may lie for a given probability level. It appears that most agricultural agencies which record rain data confine their attention to the mean of the month, season, or year. But the mean is a most unreliable guide to the capability of an area or for prediction, for in many cases the data are skewed with the mode smaller than the mean. In order for the mean to be considered a useful statistic in this context, one must also take into account a measure of the variability of the rainfall distribution.

A graphical presentation of the frequency distribution of annual or seasonal rainfall shows that the distributions tend to be symmetrical, but this is especially not so in cases where the mean is made relatively large by a few heavy falls. When seasonal and yearly rainfall totals are considered, the lack of symmetry is not critical for prediction and the distributions may be considered normal for practical purposes. However, the distribution of monthly falls is often skewed and the zero limit assumes importance. This problem has been debated by Manning [9, 10] and Glover and Robinson [4]. Manning argues that monthly rainfall is demonstrably skewed, but that the arrays may be transformed to approximately normal ones, and that the statistical estimates of the mean and standard deviation of the transformed data permit relatively accurate statements of probability. Glover and Robinson contend that the use of the transformation does not appear valid, that a single transformation does not fit different distributions, that each distribution must be considered on its own merit, and thus they advocate the simpler method of treating monthly data as if they were normal.

Two rainfall stations in St. Kitts are used to illustrate the use of the method. One of these stations has a 22-year mean of less than 100 cm (about 40 inches) and is located in a marginal, semi-arid area; the other has a 30-year mean of more than 150 cm (60 inches) and is in a wetter, sub-humid zone.[1] Table 1 presents the basic data needed for investigating

[1] These climatic divisions are after Land and Carroll [8, p.6].

Table 1. Rainfall Statistics (in CM) for Two Rainfall Stations in Different Rainfall Regimes

Month	Canada $\bar{X}$	Canada s	Belmont $\bar{X}$	Belmont s
January	6.67	4.63	9.78	4.68
February	3.64	2.49	5.88	2.76
March	3.37	2.11	6.81	7.69
April	5.59	3.45	9.51	5.55
May	9.64	9.95	16.05	11.22
June	7.40	4.51	11.82	6.99
July	9.51	4.58	12.94	4.48
August	10.49	4.66	15.08	5.95
September	12.20	5.14	20.42	8.62
October	11.12	3.53	15.93	5.77
November	11.56	4.83	16.77	8.60
December	9.25	6.03	12.24	6.94
Annual	100.44	21.27	153.22	28.56

the water availability and probability estimates for selected crop-water requirements. The growing season lasts from September to January with February marking the onset of the dry period. Even though August has a relatively high mean, this moisture goes largely to soil moisture recharge after the deficit of the dry months, and most of this is not available for plant growth. If one assumes that monthly, seasonal, and annual falls are normally distributed, it is relatively simple to establish the probability of receiving any desired amount of rainfall greater than selected minimum values. Z values can be calculated and associated probabilities of deviates found in a table of the normal distribution:

$$Z = \frac{X - \bar{X}}{s} \qquad (1)$$

where Z is the deviation from the mean in standard-deviation units, $\bar{X}$ and s are the arithmetic mean and the standard deviation respectively, and X is any individual observation.

Table 2 shows the probability of obtaining rainfall amounts higher than 2.5 cm to 12.5 cm (1 to 5 inches). For example, the probability of obtaining more than 10 cm (4 inches) at Canada estate in November is 63 per cent, and of obtaining less than 5 cm (2 inches) in January at Belmont estate is 15 per cent. It is obvious that the monthly probabilities within the season are more meaningful, for even though the seasonal total may be reliable, the month-by-month distribution may be very unreliable. The usefulness of the monthly probabilities is limited if that distribution

Table 2. Percentage Probability of Rainfall Above Selected Lower Limits in Two Rainfall Regimes

Month	2.5 cm	5.00 cm	7.5 cm	10 cm	12.5 cm
September	97*	92	82	67	48
	98	96	93	89	82
October	99	96	84	63	35
	99	97	93	85	72
November	97	91	80	63	42
	95	92	86	79	69
December	87	76	61	45	29
	92	85	75	63	48
January	82	64	43	24	10
	94	85	69	48	28

Note: *For each month, the top and botton rows refer to Canada and Belmont estates respectively.

does not coincide with the water needs of a crop or crops. However, the method can be extended to measure the reliability of any selected pattern of rainfall that is suited to any crop. If any one month's rainfall is not related to any other month's within the season, the probability that the season will receive the minimum selected pattern is calculated by multiplying all the monthly probabilities together [12]. In Table 3, selected patterns are presented for seven crops requiring arbitrarily chosen quantities of water. These monthly requirements may not be representative of any crop at all, but if actual monthly water demands are known, the probability can be computed just as easily. The monthly pattern in Table 4 represents irrigation needs for Irish potatoes[1] in Trinidad [2, p.26]. The probability of receiving this pattern of rain in a similar situation at the two estates in St. Kitts is shown. Clearly, the risks are prohibitive. Tests indicate that there is no statistical association between all the monthly rain distributions, and if there were, this method of multiplying the individual monthly probabilities would not be valid. The appropriate procedure is discussed by Clover, Robinson, and Taylor [5].

Reliability Estimates for Any Rainfall Distribution

It was stated above that the normal distribution permits reasonably reliable estimates of annual and seasonal rainfall in the more humid rainfall regimes, but previous workers in this area have agreed that when average

[1]The water requirements are not the total amount of water that Irish potatoes need for proper growth. They are irrigation needs for a particular area. It is assumed that these irrigation needs are in addition to normal rainfall.

Table 3. Percentage Probability of Rainfall Above Selected Patterns of Minimum Falls in the Growing Season for Belmont Estate

Mimumum Fall in Growing Season	September	October	November	December	Percent Probability
50.0 cm	12.5	12.5	12.5	12.5	21
47.5 cm	12.5	10.0	12.5	12.5	23
42.5 cm	10.0	12.5	12.5	7.5	33
40.0 cm	10.0	10.0	10.0	10.0	37
37.5 cm	7.5	10.0	12.5	7.5	42
35.0 cm	10.0	7.5	10.0	7.5	49
32.5 cm	10.0	7.5	7.5	7.5	53

Table 4. The Probability of Obtaining Rainfall for a Pattern of Irrigation in the Dry Season

Sugar Estates	Jan. 2.5 cm	Feb. 5 cm	Mar. 8.75 cm	Apr. 8.75 cm	May 1.25 cm	Probability
Belmont	0.9406	0.6255	0.4013	0.5557	0.9066	0.1189
Canada	0.8159	0.2877	0.0054	0.1788	0.7995	0.0002

rainfall is low, the natural lower bound of zero becomes important. These low rainfall data result in distributions that are skewed toward the larger values. However, Barger and Thom [1] have shown that the incomplete gamma-function provides a close approximation to the function F(X) irrespective of whether weekly, monthly, seasonal, or annual amounts are used. The model is flexible in its application to the monthly falls of very dry areas or to the heavy annual falls of wet regions. Where values for the mean become large in humid areas, the incomplete gamma-distribution becomes identical to the normal distribution. The incomplete gamma-function is not commonly found in statistical texts, hence the formula for estimating it will be briefly stated here.

The formal mathematical expression of this function is

(2) $$F(X) = \int_0^X \frac{X^{\alpha-1} \cdot \varepsilon^{-X/\beta}}{\beta^{\alpha} \cdot \Gamma(\alpha)} dX$$

α and β are population values that determine the size and shape of the theoretical distribution. Since the parameters α and β are unknown, statistics must be estimated from sample data. Efficient estimates of these parameters have been derived by the method of maximum likelihood [3].

(3) estimate of α:

$$g = \frac{1 + \{1 + 4/3\ (\ln \bar{X} - 1/N\ \Sigma \ln X)\}^{0.5}}{4\ (\ln \bar{X} - 1/N\ \Sigma \ln X)}$$

(4) estimate of β $b = \bar{X} \div g$

where $\bar{X}$ is the arithmetic mean of rainfall, $\Sigma \ln X$ is the summation of the natural log of X, and X can be weekly, monthly, seasonal, or annual rainfall. The value of g and b can be used to extract probabilities from tables of the incomplete gamma-function [11] in the form of u and p. These are known as the scale parameter and the shape parameter respectively. The relationship between these variables may be expressed as follows:

(5) $p = g - 1.0$

(6) $u = X \div \{b.(g^{0.5})\}$

When it is the case that the average rainfall per month, season, or year is low, there is a tendency for most of the falls to be crowded about the mean with a tail toward the larger falls. This skewness is indicative of great variability, and is also reflected in a small p or shape statistic. Similarly, in the same unit time periods of wetness, the p values become larger and indicate symmetry in the distribution. To illustrate the similarities and differences between the two distributions, reference is made to Table 5. Belmont is the station in the sub-humid zone, and October is chosen as one of the wetter months with the largest p value and smaller variability (36 per cent). The table shows that the rainfall totals about the mean have close probabilities of occurrence - or better in the case of the incomplete gamma-distribution - while toward the higher values the normal distribution tends to overestimate the probabilities that the stated falls will occur. Toward the lower zero bound the normal distribution is more conservative, but this is understandable when the shape of the two distributions is compared. In the case of Canada estate, May has the smallest p value and the greatest variability, and the greatest divergences occur at the ends. March has the largest variation at Belmont, and the differences are also apparent. Thus, in the drier months and those with greatest variability and unreliability, the normal distribution underestimates the reliability of the lower falls, and overestimates that of the falls away from the mean. Both Manning and Glover, Robinson, and Taylor warned about these extreme cases. The incomplete gamma-distribution is recommended especially in such instances, and in general where rainfall regimes tend to skewness.

The Likelihood of Given Falls in Short Periods

When the statement is made that the probability of obtaining 137.5 cm (60 inches) of rain or more annually at Belmont estate is 75 per cent, one is actually saying that *"on average"* over a very long period of time, about seven to eight years out of ten can be expected to have that minimum. However, this does not indicate the probability of obtaining 137.5 cm in seven years out of ten, nor of four years out of five. Agricultural programmes are generally geared to a period of five years, and small-scale

Table 5. Rainfall Reliability Estimates for Three Months Derived by the Incomplete Gamma-Distribution

Rainfall (cm)	Belmont October Norm. Dist.	Belmont October Incom. Gamma	Canada May Norm. Dist.	Canada May Incom. Gamma	Belmont March Norm. Dist.	Belmont March Incom. Gamma
1.25	99	100	80	94	76	94
2.50	99	100	76	80	71	84
3.75	98	99	72	73	66	68
5.00	97	99	68	67	59	58
6.25	95	98	63	56	53	44
7.50	93	95	59	51	46	36
8.75	89	91	54	42	40	27
10.00	85	86	48	38	34	22
11.25	79	79	44	31	28	18
12.50	72	71	39	28	23	13
13.75	65	63	34	23	18	10
15.00	56	50	29	19	14	7
Coef. Var. (V) =	36.22%		103.24%		112.94%	

producers hardly plan beyond that time frame. Hence, if it is established upon the basis of either the incomplete gamma-function or the normal distribution that the probability of receiving 137.5 cm or more rain annually is 75 per cent, then one can proceed to determine the likelihood of obtaining this fall in at least four years out of *any* particular five-year period. The binomial distribution is applicable in such cases [6]:

$$Pr(X) = (p + q)^n \tag{7}$$

where p is the probability of receiving X cm, q = 1-p or the probability of not receiving X cm, and n is the number of years in the time period considered. Since p = 0.75 (or 75 per cent), q = (1.0 - 0.75) = 0.25, and n = 5, Equation (7) can be expanded to

$$(p + q)^5 = p^5 + 5p^4q + 10p^3q^2 + 10p^2q^3 + 5pq^4 + q^5. \tag{8}$$

The first and second terms on the right give the probability that all five years and four years will receive the stated amount respectively, and the last term gives the probability that no year will receive it. The likelihood that at least four years in five will receive 137.5 cm or more at Belmont is

(9) $\quad p^5 + 5p^4q = 0.75^5 + \{5(0.75^4)(0.25)\}$

$$= 0.6328 \text{ or } 63\%$$

and the probability of at least 112.5 cm (45 inches) at Canada in at least four out of five years - the probability of at least 112.5 cm annually being 50 per cent - is 18 per cent. The risks of planting for farmers in either region is obvious.

The binomial distribution has other possibilities for agricultural planning - either to reduce loss or increase production. If it is required to know the probability that any two of three successive years will have or not have a desired fall, expansion of this term will provide a guide. For two successive years it is

(10) $\quad (p + q)^2 = p^2 + 2pq + q^2$

The probability that Belmont will receive 137.5 cm to two years or three years in a row is $(0.75)^2$ or 0.56 and $(0.75)^3$ or 0.42 respectively, and of not receiving that amount in three consecutive years is $(0.25)^3$ or 0.06.

Summary and Conclusion

Rainfall in the Caribbean is marked by a general seasonal pattern of heavy rain when the maritime tropical air masses predominate in the last quarter of the year, and of light rain from February to April during the period of low sun. In planning for agricultural development, planners and practical agriculturalists who are interested in minimising crop loss or increasing output will achieve limited success by use of rainfall totals and the mean of monthly, seasonal, or annual periods. These statistics are most unreliable especially in marginal districts or relatively dry areas, and the variability of such falls must be taken into account.

In general, seasonal and annual rainfall can be assumed to be normally distributed, and from the computed mean and standard deviation, it is a simple matter to establish the confidence or fiducial limits within which any rainfall observation will lie. Once the monthly probabilities are established, the probability of obtaining any monthly pattern within a season that conforms to the water demands of a crop can be calculated by multiplying the several probabilities (when there is no statistical association between the months).

Evidence has shown that the distribution of weekly and monthly falls and of annual falls in dry areas tend to skewness with a clustering of the values about the mean, but with a few large falls above the mean. In such cases, the use of the normal distribution model for prediction raises the serious question of validity, and the incomplete gamma-distribution is the preferred model. It provides a satisfactory approximation for rainfall whether weekly, monthly, seasonal, or annual amounts are used for arid, semi-arid, or humid regimes. In the latter case, it is identical with the normal distribution.

When the reliability of rainfall within confidence limits has been assessed, one is at best making an expression of the *"average"* conditions over a long period, like 30 years or more. The farmer and practical agriculturalist are more likely to be interested in a short period assessment, such as the likelihood that in any n-year period 1, 2, or n of those years will have enough rain for his crops. The binomial distribution provides such answers. From the same distribution, one can determine the likelihood that any 2, 3, or n successive years will obtain less than or more than a specified fall.

These techniques offer great potential for future crop production in the Caribbean, and as in East Africa, they can make a valuable contribution to the agricultural development effort. However, these methods alone will only realize their potential when combined with information from the agronomist or agro-meterologist on evaporation, evapotranspiration, and potential evapotranspiration rates of common Caribbean crops.

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