THE JOURNAL OF AGRICULTURE
OF THE UNIVERSITY OF PUERTO RICO

Issued quarterly by the Agricultural Experiment Station of the University of Puerto Rico, for the publication of articles by members of its personnel, or others, dealing with any of the more technical aspects of scientific agriculture in Puerto Rico or the Caribbean Area

Vol. LX | APRIL 1976 | No. 2

On the Climate of Puerto Rico and its Agricultural Water Balance[1]

Modesto Capiel and Robert J. Calvesbert[2]

ABSTRACT

A brief appraisal of the climatic and related agricultural hydrology aspects of Puerto Rico is discussed. In the tropics moisture and latent heat flux cycles are generally more critical than temperature (sensible heat flux) in contrast to these relationships at middle and higher latitudes. Yet, a continental-like climate is found in some interior valleys such as at Utuado, where the daily air temperature span is around 22°C in winter.

A low level inversion (trade-wind inversion) is generally exhibited below 2 km, constituting a most important regulating valve of the general circulation here. Frequently, it acts as a strong lid opposing the vertical cloud development necessary to produce rainfall. This undesirable situation possibly makes things worse in the drier part of the year, producing wide statistical spread from the mean rainfall at that time.

An appraisal of the Island's hydrology reveals a very unfavorable agricultural water balance for the south coast, in contrast to a decidedly better picture for the north coast. Nevertheless, during the past decade both the north and south coasts experienced a build-up of the most extreme drought conditions in the history of the island. The Palmer's Drought Index, which coincides with the gap between actual and potential evapotranspiration, shows that 1964, 1965, 1967, and 1968 were the most critical years. Application is made of the Crop Moisture Index (CMI) as a more detailed measure of drought in the time scale.

GENERAL ASPECTS

Climate is generally thought to exert a great influence on biological phenomena. As far as crops are concerned, this influence is generally

[1] Submitted to Editorial Board November 22, 1974.

[2] Agricultural Climatologist, Agricultural Experiment Station, University of Puerto Rico, Mayagüez Campus, and formerly, NOAA-National Weather Service Climatologist for Puerto Rico and the U.S. Virgin Islands, respectively.

coupled with a simplified term known as "seasonal effects". In the tropics, however, the seasons, as they are known elsewhere, are not clear-cut, mainly because temperature changes throughout the year are relatively insignificant.

As an example, the term "fall" as synonymous with "autumn" does not make sense in Puerto Rico. True fall conditions here are associated with onset of the spring months. The general tree leaf abscission that occurs in the Caribbean beginning in early April is possibly explained by the fact that atmospheric and soil moisture levels decrease rather sharply and simultaneously with an increase in soil and air temperature during that month. This establishes a break from the preceding winter months with a more favorable water balance, resulting in a sudden lag in root absorption beyond transpirational demands.

Therefore, in contrast to the middle and higher latitudes, the moisture and latent heat flux cycles are generally more critical in the tropics than temperature (sensible heat). Thus, in Puerto Rico, as in all tropical zones, the seasonal rhythm which so strongly patterns life in mid-latitudes becomes less clear-cut. From a temperature standpoint, the growing season lasts throughout the year. The sun reaches the zenith twice annually, as in all of the tropics. Since the solar position changes only gradually at the solstices, the time spent by the sun going poleward is relatively short and during 2 months and 20 days (between May 12 and July 31) the sun is almost constantly overhead. Thus, as the sun rises and falls from the zenith it provides little margin for seasonal temperature fluctuations.

The physiography of the land is an important factor influencing variations in the mean air temperature. While seasonal fluctuations on a given area span 4° to 5° C between the warmest and the coolest months, the mean variation among regions within a given month may reach 7° to 8° C as a result of elevation differences.

PHYSICAL CHARACTERIZATION

AIR TEMPERATURE

Puerto Rico lies between latitudes 18.00° and 18.30° N. This narrow difference between north and south (0.3°) is sufficient to permit a thermal characterization of regions by mean monthly air temperature, as described in figure 1 for the north and south coastal regions, as well as for the mountain region. The temperature values were averaged up to 1970 from data of representative stations in the indicated regions having long-term records of from 20 to 70 years (6, 7). The mean monthly temperature of two interior valleys in the mountain ridge (Utuado and Caguas) are also illustrated in figure 1.

The greater gap between the maximum and minimum temperature all through the year in Utuado makes this region more closely resemble a continental type of climate than the other regions described in figures 1, 2, and 3. On the other hand, the north and south coastal regions with typical maritime climate maintain an approximate difference of about 2° C throughout the year, with the south coast being the warmer of the two. This is because of the generally drier soils in the south, in addition to a warmer air drainage or advection from the southern ridge of the mountain range at nighttime. Although the upward sensible heat flux is of

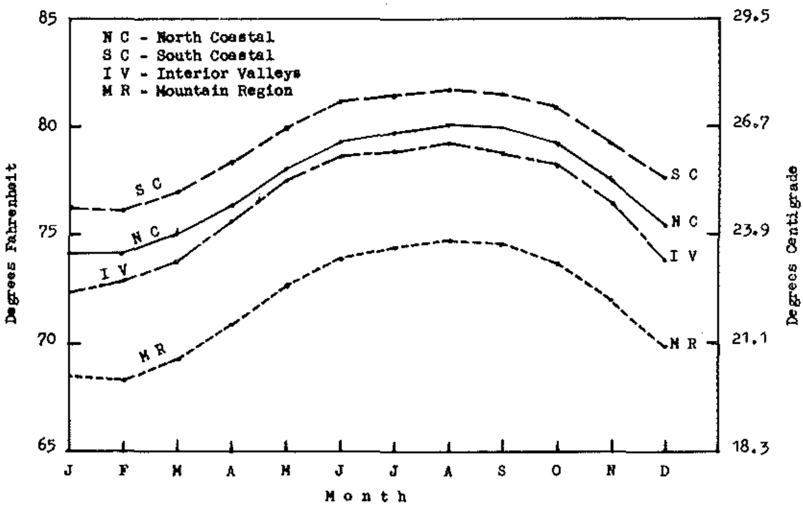

FIG. 1.—Mean monthly temperature of different geographic regions of Puerto Rico.

greater magnitude along the south coast, the sea breeze on both coastal areas tends to mask the difference during daytime. For this reason the interior valley of Utuado, with a higher elevation than the coastal regions (Ponce and Manatí), attains a higher maximum air temperature most of the year (fig. 2). Otherwise, the mountain region exhibits a lower maximum temperature as a result of the higher elevation (fig. 2). A difference of 215 m in elevation between Aibonito and Los Guineos results in a temperature difference of about 2°C, or nearly 1.1°/100 m. However, observed low level inversions and physiographic conditions of the mountain area do not permit lapse rate interpretations.

The minimum air temperatures (fig. 3) suggest that Utuado, with its continental-like climate can meet optimum environmental conditions for a diversified vegetable and ornamental horticulture, possibly better than other agricultural areas of Puerto Rico. It has the widest span in daily air temperature on the island, about 16° and 22° C in summer and winter, respectively. This is twice as much as that of San Juan. Sweet peppers, for example, can be grown with greater success in this area because of a longer fruit-set period (longer span of required minimum night temperature). The same applies to tomatoes. With this in mind, figures 2 and 3 also include Utuado as an example of a specific interior valley site. There is no available climatic data for the smaller valley of Jayuya although this location was very popular some years ago for its production of

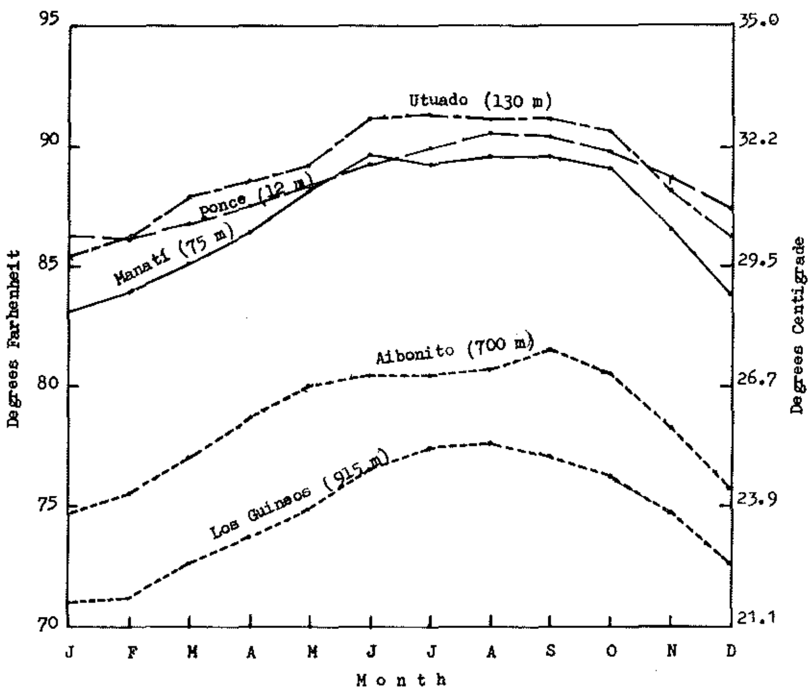

FIG. 2.—Mean monthly maximum temperature of representative locations in the different geographic regions of Puerto Rico.

tomatoes. It is indeed interesting that the Utuado Valley, around 570 m lower than Aibonito in elevation, exhibits lower minimum temperatures than Aibonito, in spite of its much higher maximum temperature at midday, even higher than the maximum at Ponce in summer. In general, although temperature and elevation are inversely related, minimum temperature is less related to elevational effects than maximum temperature. This is because of cool air drainage into the lower valleys.

RAINFALL

In Puerto Rico the moisture cycle, rather than the temperature, is the controlling seasonal factor; and the concept of dry and rainy seasons replaces the four-season temperature cycle of middle latitudes. In the Caribbean the structure of the atmosphere exhibits a temperature inversion in the lower atmosphere, generally below 2 km (trade-wind inversion). Below this inversion the atmosphere is quite moist, filled with cumulus clouds, and the lapse rate is steep. Above the inversion the air is very dry. Puerto Rico is on the western end of the easterly trade wind belt where the inversion frequently extends at relatively low levels over the western part of the ocean in the dry season (December to April). This inversion is perhaps the most important regulating valve of the general circulation. It acts as a strong lid to oppose vertical cloud development which is necessary to produce rainfall.

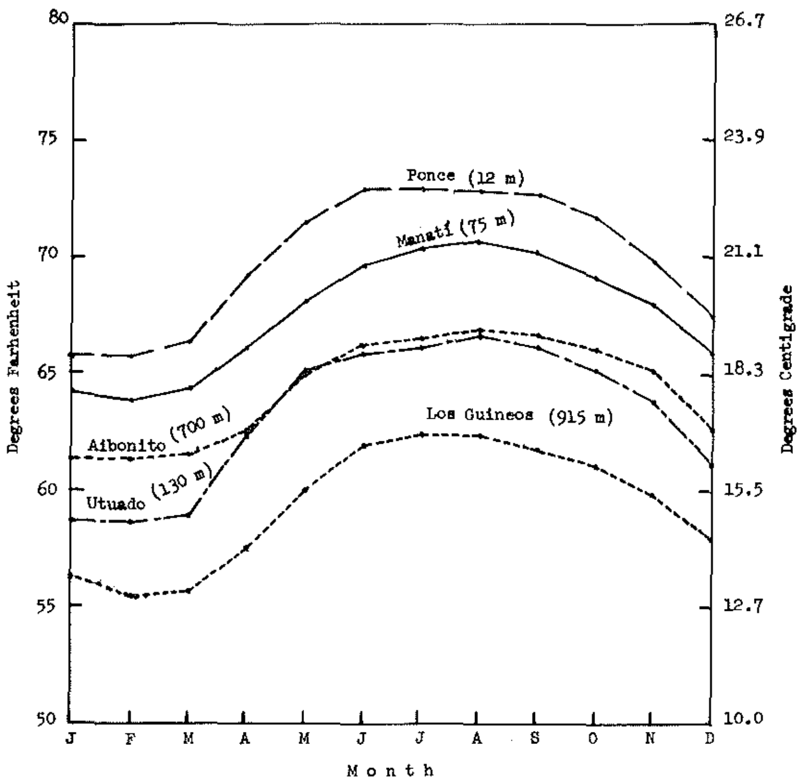

FIG. 3.—Mean monthly minimum temperature of representative locations in the different geographic regions of Puerto Rico.

On the other hand, waves in the easterlies and other synoptic disturbances over Puerto Rico produce a broad summer rainfall peak. The hurricane influence is less than is often assumed because hurricane frequency and rainfall are not correlated. Often, more rain falls on days with a rather weak circulation than during hurricane passages. There are stations with double peaks, however, with no relation to the equatorial trough type of rainfall. This is especially noticeable in the mountain region, as shown in figure 4.

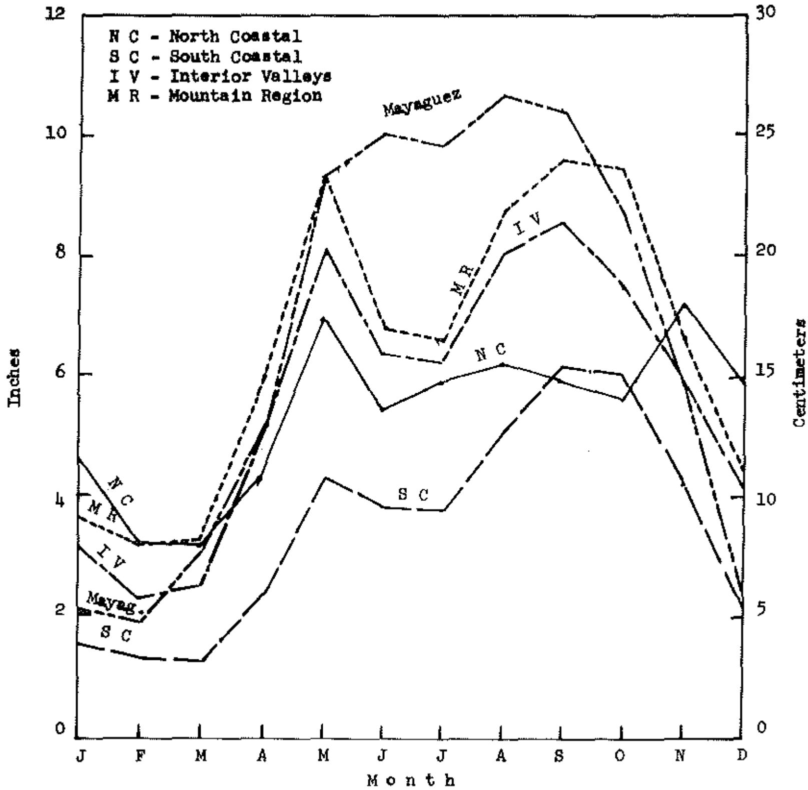

FIG. 4.—Mean monthly rainfall of different geographic regions of Puerto Rico.

The monthly or weekly rainfall distribution at specific locations, similar to many other areas, commonly has a wide statistical spread which is not normally distributed about the mean but highly skewed. Moreover, the mean deviations from the mean rainfall are greatest in months of least rainfall. As an example, it was found (2) that the coefficient of variation of the least rainfall in 4 months is 37% greater than that of the maximum rainfall in 3 months in east and east-central

Puerto Rico although greater variability should be expected in the shorter period. This is frequently a basic cause of crop failure under nonirrigated conditions in the north coast, east-central, and mountain regions.

Yet, an agricultural water balance approach in the north coast region does not reflect water deficits during the year (fig. 5). Only from February to April (and to some extent in June) water is drawn from storage without apparent curtailment of the water reservoir. This water balance represents a mean long-term condition of the north coastal zone of Puerto Rico, including stations representing sub-humid to wet conditions judged by their annual rainfall. Therefore, figure 5 should not

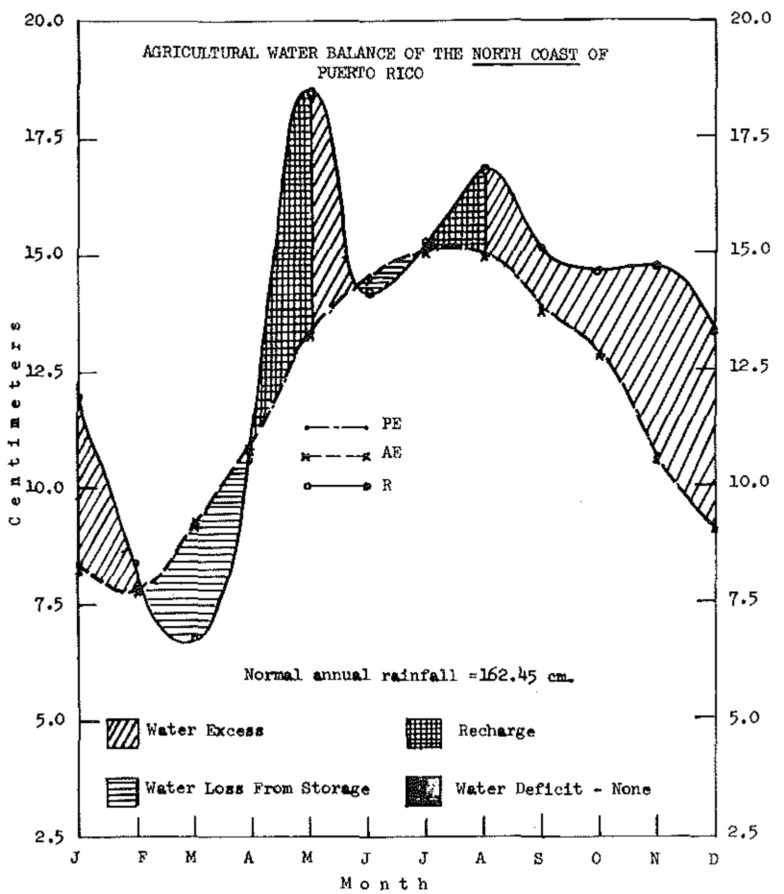

FIG. 5.—The agricultural water balance of the North Coast of Puerto Rico, based on mean monthly values of rainfall, potential and actual evapotranspiration.

be appraised by a particular farmer on a given farm of the north coast, particularly for a limited number of years.

In the south coastal area drought conditions are most critical because of deficient rainfall, generally averaging less than 10 cm during 6 months of the year (fig 6). Rainfall deficiency becomes most critical in June and July since higher temperatures and longer days accompany these droughts. Islandwide, the February, March, and April rainfall is generally lowest, however. Strong winds and increasing evaporation rates complicate the problem of low rainfall during these months.

The north coast receives less than 10 cm of rainfall per month only in February and March. However, in the tropics much more water is needed to keep the fields moist than in middle latitudes. This is especially true

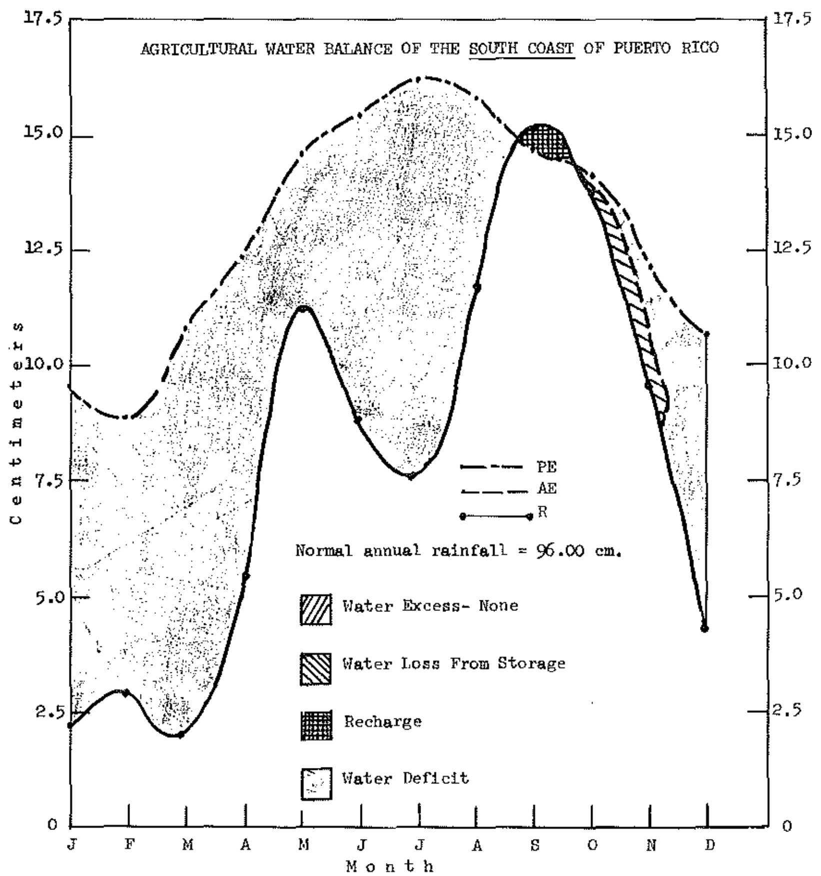

FIG. 6.—The agricultural water balance of the South Coast of Puerto Rico, based on mean monthly values of rainfall, potential and actual evapotranspiration.

for growing vegetable crops. The water storage capacity of most soils of this area is limited by a shallow root zone and by frequent erosion caused by intense showers on sloping land.

The Mayagüez area rainfall is a magnified projection of the south coast rainfall pattern. It is very deficient in the first 3 months but has a broad peak extending from May to October. This makes the west coast the second most badly distributed rainfall region on the island after the south coast. In many areas of Puerto Rico from 40 to 45% of the annual rainfall is received in just 3 months, with the south coast receiving the greatest proportion in this period.

APPRAISAL OF THE HYDROLOGIC SITUATION

AGRICULTURAL WATER BALANCE

There is great contrast between the agricultural water balance for the north and south coasts of Puerto Rico under normal monthly temperature and rainfall conditions as shown in figures 5 and 6. The south coast conditions clearly call for supplemental irrigation for any crop most of the year. Soil recharge is too limited to allow water to be drawn from storage more than 2 to 3 months of relatively low evaporative demand.

On the other hand, the north coast picture reflects an excess of water (saturated soils) in 6 out of the 12 months of the year. No water deficit occurs in any month of the year because, as an average, there is year-round sufficient soil moisture to meet the potential evapotranspiration needs.

However, figures 5 and 6 are based on three assumptions that present a rather optimistic water balance picture. The first one, related to the actual evapotranspiration (AE), allows for an active root-zone depth with a total available moisture of 15 cm. Second, a two-layer system of soil moisture depletion is applied. The upper layer, or plow-depth layer of soil moisture, is assumed to be depleted at the potential rate, as determined by Thornthwaite and Mather (5). Any deficiency in this layer must be satisfied before rainfall begins to recharge the second layer below. The remainder of the available moisture in this underlying layer (12 cm) loses moisture only when there is none in the plow layer above. In this case evapotranspiration is no longer at the potential rate; it is assumed to be directly proportional to the available water holding capacity of the soil system. Third, runoff is granted only after both layers reach field capacity. This assumption, of course, has limitations as Palmer has pointed out (3).

The agricultural water balance approach represents crop-water relations to the degree in which the normal rainfall can represent actual values. In the south coast area the absolute deviations from the normal are generally of less magnitude than in the north coast region. Therefore, the north coast values can be accepted only with certain reservations. They have better application for orchards, vines and deep-rooted crops in general. Also, a good part of the north coast towards the eastern end of the island overweighs the normal monthly rainfall for that climatic division.

On the other hand, it is obvious from figure 6 that on the south coast nonirrigated crops are less than a marginal operation even under a normal rainfall regime. Extended periods of below normal rainfall result in even higher water deficits, which place irrigation sources in critical supply and cause serious havoc to nonirrigated crops in the north.

DROUGHT SEVERITY

The last decade saw the build-up of the most extreme drought conditions in the history of the island. Figure 7 presents the complete drought cycle as experienced in the north and south coastal areas from the early months of its inception in late 1963 to the final return to near normal conditions by late 1970. The shaded area represents the calculated water deficit by months, based on the difference between the potential evapotranspiration rate (solid line) and the actual evapotranspiration (broken line), as obtained from the monthly water balance. Where the shaded area blends into a single line, the water need is met. The large dots indicate the value of the Palmer Drought Index (PDI). The index is a numerical value generally ranging from about +6 to −6. Positive values indicate the degree of abnormally wet weather and negative values show the intensity of abnormally dry conditions, in accordance with the following descriptive terms:

Scale	*Degree of wetness, or of drought*
4.00 or more	Very much wetter than normal
3.00 to 3.99	Much wetter than normal
2.00 to 2.99	Moderately wetter than normal
1.00 to 1.99	Slightly wetter than normal
.50 to .99	Incipient wet spell
.49 to −.49	Near normal
−.50 to −.99	Incipient drought
−1.00 to −1.99	Mild drought
−2.00 to −2.99	Moderate drought
−3.00 to −3.99	Severe drought
−4.00 or less	Extreme drought

Details of Palmer's Drought Index computation have been published by Palmer (3). The difference between a computed rainfall amount

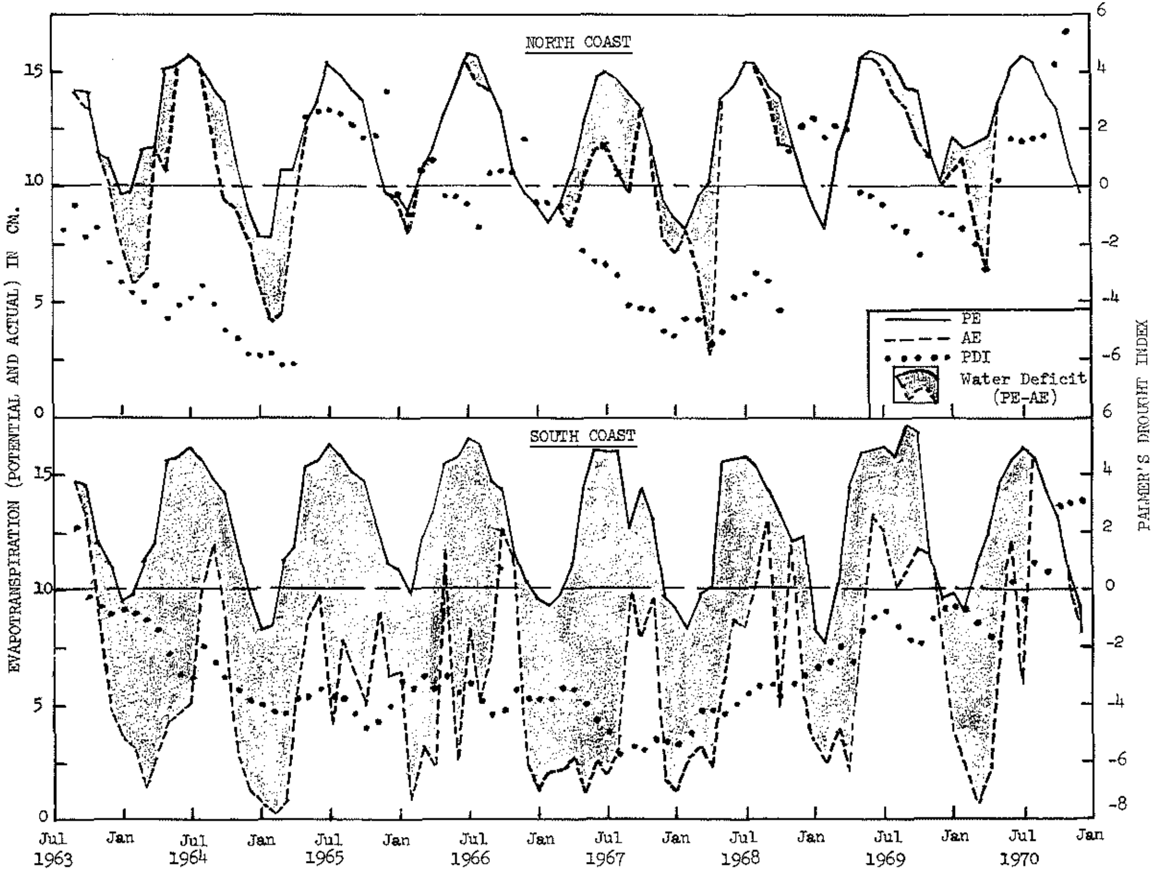

FIG. 7.—Build-up of a water deficit in the North and South Coasts of Puerto Rico from July 1963 to December 1970.

climatologically appropriate for the area (to sustain normal evapotranspiration, runoff and moisture storage levels) and actual rainfall is empirically adjusted on an accumulative basis from month to month to produce a numerical value which falls on the scale previously described.

The history of meteorological drought in Puerto Rico has been brought out by Calvesbert (1). Although Palmer had reservations concerning the applicability of the Index to humid areas because of the generally limited water storage capacity of its soils, Calvesbert (1) reports that he obtained reasonable values of the PDI by assuming that the water storage capacity of the south coast soils is 15 cm instead of 10 cm.

The concept of drought severity as a meteorological anomaly, characterized by prolonged and abnormal moisture deficiency, is considered in the PDI not only from the standpoint of moisture supply but of moisture demand. The quantitative index resulting from this approach has significant correlation with the more restrictive concept of agricultural drought. At the same time the complications of biological response inherent in the aspects of agricultural drought are purposely avoided.

Palmer attempted to define the significance of the drought severity classes in terms of drought effects on the economy (3):

> "One can, as a rule of thumb, regard incipient drought as corresponding to a sort of dry spell in which the need for rain becomes definitely apparent. Extreme drought, on the other hand, is a very serious situation which results from many months, or even years, of abnormally dry weather. Very rarely, if ever, would one find drought reaching extreme severity in less than 4 months. During extreme drought, crop yields are ordinarily so low that the crop is considered to be unprofitable; industries and municipalities may face the need for rationing water, and the local and regional economy begin to become disrupted. So extreme drought is not merely an inconvenience; it is essentially a disaster."

Figure 7 illustrates the build-up of a long-term water deficit in the north and south coastal divisions in the proportions described graphically. The extreme drought classification was finally reached by late 1964 and early 1965, and the effects were remarkably parallel to those quoted above. Minor crops were of poor quality and in short supply. Irrigation in the south coast was reduced to 25% of normal. South coast cattle areas were hit hard with water supply trucked in from the north and grain and molasses shipped in from the United States; many cattle still died in the fields. Sugar yields, already in a steadily declining trend from below the million-ton mark by the early sixties, attained the most dramatic yield drop following the 1964 and the 1967 droughts. Generation of electricity by hydroelectric plants dropped to 5% of the total power output while the thermoelectric plants provided 95%. By March 1965 the San Juan metropolitan area went on daily water rationing; other areas had been on a tight ration basis months prior to this. Ground water levels along the south coast dropped 1 to 3 m in unpumped areas and more in pumped areas. It was obvious that the drought intensity in Puerto Rico had made the full progression from the inconvenience stage to disaster proportions.

Evidence of the need for climatic adjustment factors built into the PDI computations is seen from the fact that although the water deficits on the north coast were considerably less, the drought intensity values equaled and at times exceeded the south coastal condition. This was the situation in 1964 and again in 1967. It can be further seen that while in the prolonged drought in the south coast, there aroused a break on the north as a result of the heavy May rains in 1965 on this side. The year 1966 provided adequate moisture on the north side but continued with extreme drought along the south until about the middle of 1967 when both coasts again went into severe drought conditions. The year ended with a record low annual total rainfall at many southern stations, as little as 25% of normal. Even the passage of hurricane Beulah, with over 12 cm of rain in some areas during September, failed to provide significant relief. As the deficit continued into 1968, alluvial aquifers reached all-time lows, and some static water levels were below sea level in areas of heavy withdrawal. Emergency funds were made available again to farmers and dairymen who were suffering heavy losses. Finally, on the north coast the spring and early summer rains of 1968 once again erased the long-term water deficit and the balance returned to normal. In the south coast the agricultural drought was greatly eased by the summer rains of 1968 and water deficits began to decrease. The Index in this area still hovered around the incipient to the mild drought level through 1969. The summer and fall rains of 1970 finally ended the cycle, which was one of the longest and most severe droughts on record.

The monthly water balance, in conjunction with the development of Palmer's Drought Index, has made possible a stronger grasp on the climatology of meteorological drought in Puerto Rico and a means of identifying the beginning and ending of significant drought periods. On the other hand, on a comparative yearly basis Capiel's DEF and DIS (2) provide useful numerical inventories of rainfall characteristics as to deficiency and distribution.

Palmer has also developed an additional technique which provides for a faster reacting index suitable for following the levels of moisture that may still be available to growing crops on a weekly basis (4). Again, the same water balance approach as that for the Palmer's Drought Index is used. Briefly, the Crop Moisture Index (CMI) is made up of essentially two terms: the evapotranspiration anomaly and a wetness factor. The first term—the evapotranspiration anomaly—is a cumulative measure by which the weekly evapotranspiration for the division has departed from an adjusted normal. This term (usually negative) is calculated on the basis of the actual temperature and rainfall during the week, as well as a consideration of the computed soil moisture at the start of the week. As this accumulated evapotranspiration deficit increases (becomes more negative) from week to week during dry weather, the crop moisture situation becomes more serious. Since it is sometimes too wet for crops as well as too dry, a second term making up the formula for the estimation of CMI is a measure of excess wetness, which occurs when heavy rains make the soil too wet for field operations, and perhaps cause minor flooding. In this case soil moisture recharge and surface runoff are considered. The algebraic sum of these two terms—the evapotranspiration anomaly and the wetness factor—make up the final Crop Moisture Index.

The CMI must be interpreted in terms of the definitions shown in table 1. The descriptions were originated for growing crops in the temperate zone. Although the Index is by no means perfect, it appears to present a reasonable estimate of crop moisture conditions in the tropics in spite of some of the assumptions involved. There is a choice of interpretation to make, depending on whether the area in question was drier or wetter than the previous week (table 1). Negative values of CMI always mean

TABLE 1.—*Legend of the Crop Moisture Index descriptive for weeks with greater or less added soil moisture (from rainfall) than the previous week*

Index decreased during week		Index increased or did not change during week	
Index	Situation	Index	Situation
3.0 or greater	Some drying, but still excessively wet.	3.0 or greater	Excessively wet, some fields flooded.
2.0 to 3.0	More dry weather needed, work delayed.	2.0 to 3.0	Too wet, some standing water.
1.0 to 2.0	Favorable, except still too wet in spots.	1.0 to 2.0	Prospects above normal, some fields too wet.
0 to 1.0	Favorable for normal growth and field work.	0 to 1.0	Moisture adequate for present normal needs.
0 to −1.0	Topsoil moisture short, germination slow.	0 to −1.0	Prospects improved, but rain still needed.
−1.0 to −2.0	Abnormally dry, prospects deteriorating.	−1.0 to −2.0	Some improvement, but still too dry.
−2.0 to −3.0	Too dry, yield prospects reduced.	−2.0 to −3.0	Drought eased, but still serious.
−3.0 to −4.0	Potential yields severely cut by drought.	−3.0 to −4.0	Drought still severe, rain urgently needed.
−4.0 or less	Extreme drought, most crops about ruined.	−4.0 or less	Not enough rain, drought still extreme.

that evapotranspiration has been abnormally deficient. Positive values mean that either the actual evapotranspiration exceeded the expected amount, or that recent rainfall exceeded the moisture requirements of crops, and the additional water was added to the soil or was considered as runoff.

When studied in detail at one particular location, the problem of agricultural drought is highly complicated by such factors as local differences in soils and crops, root-zone depths, and stage of crop growth. All these elements were also neglected by Capiel and Antoni (2) in developing rainfall distribution and deficiency indices (DIS and DEF) for two locations in Puerto Rico. Similarly, in resource planning and in the inventory stage, their consideration is somewhat beyond expectation. The CMI did not account for these edaphic factors; it was built to provide some useful information on the crop moisture situation in a general region rather than localized individual locations. As such, it is based on reports of average temperature and average rainfall conditions in six divisions of Puerto Rico. This Index (CMI) is published weekly in "Clima y Cosecha" by the Commonwealth Department of Agriculture and provides a most useful means of evaluating the availability of moisture for meeting current demands of a growing crop.

RESUMEN

Se realizó un breve análisis de las características climáticas e hidrológicas de Puerto Rico, interrelacionadas entre sí. Mediante la selección de estaciones típicas de las regiones norte, sur, central, valles interiores y del oeste, se presenta el curso anual de las temperaturas máximas y mínimas medias, así como el correspondiente cuadro pluviométrico. Todos los valores presentados representan promedios mensuales hasta 1970, inclusive, (20 a 70 años).

Se discute brevemente la incidencia de sequías y se ofrece un enfoque agrícola del balance hidrológico. Se discute, además, la aplicabilidad de índices representativos de la disponibilidad de lluvia para las cosechas.

LITERATURE CITED

1. Calvesbert, R. J., Climatology of meteorological drought in Puerto Rico, Proc. Conf. on Climatology and Related Folds in the Caribbean, Mona, Jamaica, Sept. 1966.
2. Capiel, M., and Antoni, M., Two rainfall characteristic indices proposed as suitable for agricultural planning in Puerto Rico, J. Agr. Univ. P.R. 57 (1): 24-41, 1973.
3. Palmer, W. C., Meteorological drought, Res. Pap. No. 45, U.S. Weather Bur., Feb. 1965.
4. Palmer, W. C., Crop moisture index, Weekly Weather and Crop Bull., April 1968.
5. Thornthwaite, C. W., and Mather, J. R., Instructions and tables for computing potential evapotranspiration and the water balance, publ. Climatol. 10 (3), Drexel Inst. Technol., Lab. Climatol., Centerton, N.J., 1957.
6. U.S. Weather Bureau, Climatological data—Puerto Rico and U.S. Virgin Islands, 1961-70.
7. U.S. Weather Bureau, Climatic summary of the U.S., Puerto Rico, and Virgin Islands, Suppl. 1951-1960.