

An application of Palmer's drought index to a semi-arid tropical region

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Abstract

Palmer's Drought Index (PDI) was applied to a semi-arid region in Costa Rica. In the computations of the water balance, two modifications to Palmer's method were made. The method of Hargreaves was used to obtain potential evapotranspiration and the procedure of Thorntwaite and Mather to obtain potential runoff.

The period of analysis in the region was from June 1972 to December 1983 (i.e. 138 months), of which 32% had drought conditions, with 7% mild, 11% moderate, 11% severe, and 3% extreme droughts (according to Palmer's classification). The values obtained for the PDI were tested against reports from the press concerning crop damage by droughts and a very good agreement was found.

The dependence of the PDI on the available water capacity of the soil and the potential evapotranspiration is also discussed.

Introduction

Droughts and floods are the result of extreme fluctuations in the water balance. They produce economic losses because of their effects on the agricultural and industrial activities and, in the case of droughts, on the supply of water as well.

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Drought has been defined in several ways, most of the definitions taking into account its effects rather than its causes. Palmer (1965) defines drought as "an interval of time, generally of the order of months or years in duration, during which the actual moisture supply at a given place rather consistently falls short of the climatically expected or climatically appropriate moisture supply". Commonly, a distinction between dry spell and drought is made. The former consists of a few weeks in which rainfall is small or null, and the latter consists of a relatively long period with deficiency of rainfall (but not necessarily lack of rain).

Palmer (1965) developed an index of drought severity, referred here as Palmer's Drought Index (hereafter PDI), which allows comparisons to be made in time and space of drought severity; in the PDI a weighting factor is applied to the different deviations of humidity in order to have comparative indexes. In this way, PDI gives an objective evaluation of the degree of severity, which depends largely on the duration and intensity of the deficiency of humidity. When the climatic conditions are persistently normal, the value of the PDI is zero; if there are humidity fluctuations its value varies in general from 6 to -6 depending of the degree of severity, taking positive values under anormally humid conditions and negative values under anormally dry conditions. According to the PDI values, Palmer made a classification of anormally dry and humid periods (see Table 1). He applied his method to the regions of Western Kansas, Central Iowa, and Northeastern North Dakota in the United States and found good agreement between the PDI values and observations.

Table 1
Classes for wet and dry periods, according to the values (X) of
the PDI (from Palmer, 1965)

| X | Class |
|----------------|---------------------|
| ≥ 4.00 | Extremely wet |
| 3.00 to 3.99 | Very wet |
| 2.00 to 2.99 | Moderately wet |
| 1.00 to 1.99 | Slightly wet |
| 0.50 to 0.99 | Incipient wet spell |
| 0.49 to -0.49 | Near normal |
| -0.50 to -0.99 | 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 | Extreme drought |

In this paper, we will calculate the PDI for a semi-arid tropical region and we will evaluate the results by comparing them with press reports of crop damage.

Region of study and data

Figure 1 shows the location of the region of study, a semi-arid relatively flat region with maximum altitudes of about 100 m and located in Guanacaste, (Pacific side of Costa Rica). This region was chosen because it is predominantly agricultural and is the part of Costa Rica most affected by droughts. In order to make the data processing easier and to determine some possible spatial variations, the region of study was divided into two areas, namely areas 1 and 2 (Figure 1). The meteorological stations used in this study are also shown in Figure 1. The period of analysis is from June 1972 to December 1983 (i.e. 138 months).

Herrera (1984) made an evaluation of the state of crops using agrometeorological techniques and he showed values of PDI for Liberia and Nicoya meteorological stations; Liberia station being located in our region of study. However, our interest here is in computing the PDI for areas 1 and 2 rather than for single stations, except for the analysis of the areal distribution of the PDI in Section 4 and for the discussion of the dependence of the PDI on the potential evapotranspiration in Section 6.

Figure 2 and 3 show the distributions of average monthly values of some meteorological variables at Liberia and Taboga stations, which are representative of areas 1 and 2, respectively. The potential evapotranspiration was obtained with the method of Hargreaves, which will be discussed later. A rainy season from the middle of May to the middle of November and a dry season for the rest of the year can be distinguished; May and November are regarded as months of transition and July as the month of a relative rainfall minimum known as "veranillo". The monthly rainfall maximum occurs in September, a characteristic of the semi-arid zone of Central America; in other parts of the Pacific side of Central America the rainfall maximum occurs in October. The mean annual rainfall totals for both Liberia and Taboga are 1666 mm. As expected, the potential evapotranspiration is larger during the dry season and the veranillo than during other times of the year. The average annual temperature for Liberia and Taboga is 27°C. During the dry season the average monthly values of the relative humidity are of the order of 65% and the predominant winds are the northeasterly trades with an average monthly speed of about 5 ms⁻¹; some gusts may reach speeds of about 30 ms⁻¹. During the rainy season the average relative humidity is about 80% and the average wind about 2 ms⁻¹. The trades are weaker during this period thus allowing the penetration of the equatorial westerlies and the sea breeze. These provide the necessary humidity for the production of rains.

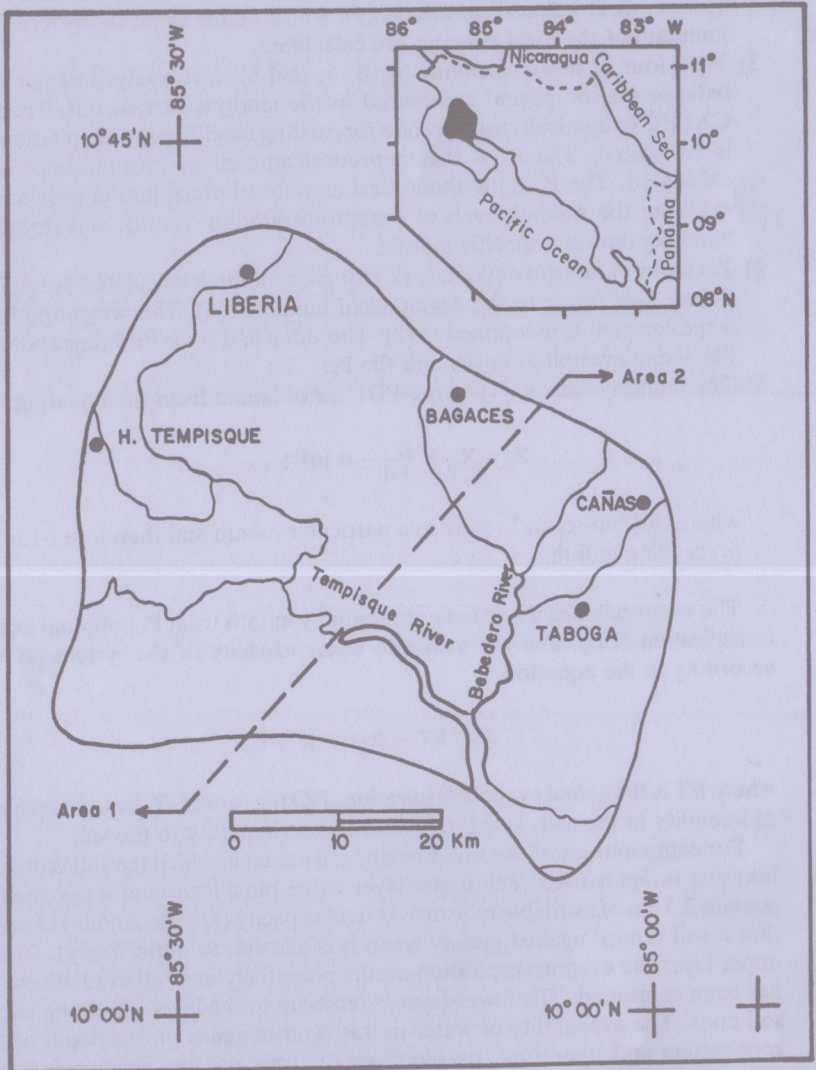


Figure 1. Map of the region of study (the limits are schematic), showing the location of the meteorological stations.

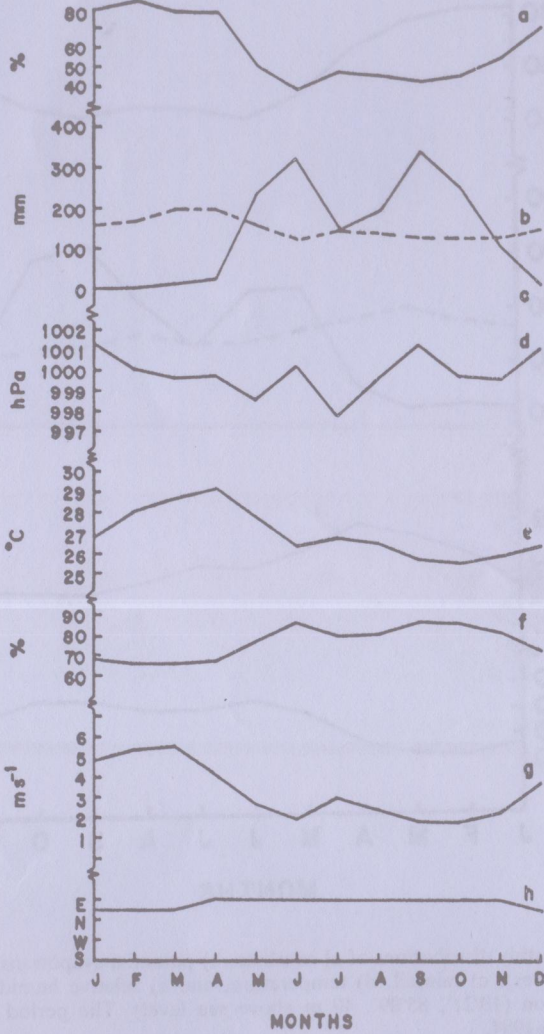


Figure 2. Monthly distributions of a) sunshine, b) potential evapotranspiration (Hargreaves), c) rainfall, d) pressure, e) temperature, f) relative humidity, g) wind speed, and h) wind directions at Liberia station (10°37', 85°26', 144 m above sea level). The period of analysis is 1976-1984.

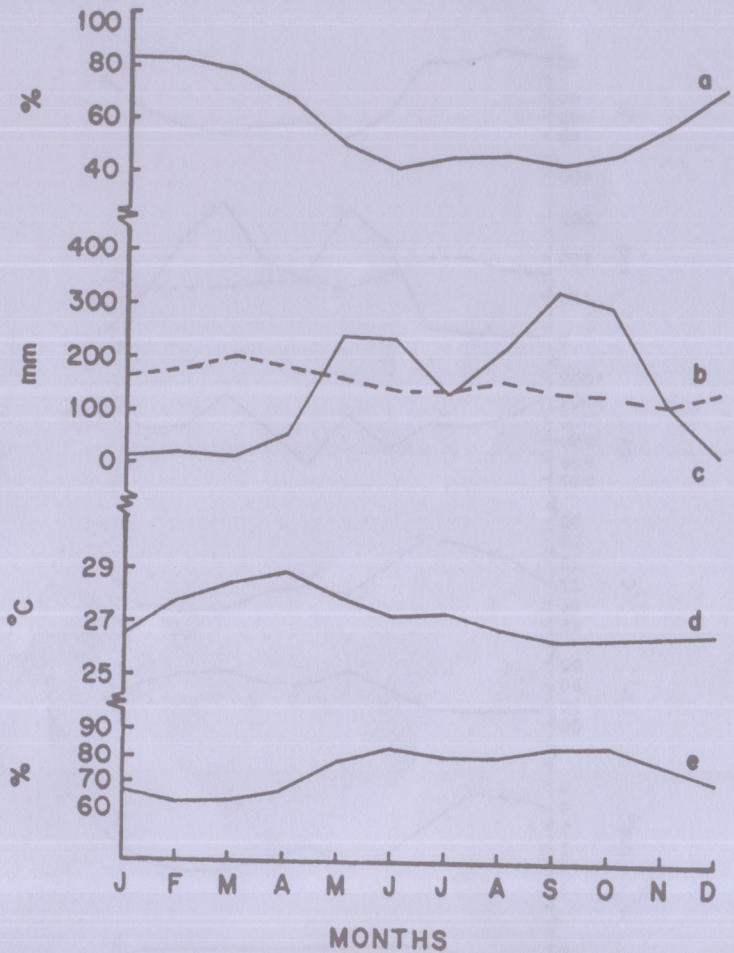


Figure 3. Monthly distributions of a) sunshine, b) potential evapotranspiration (Hargreaves), c) rainfall, d) temperature, and e) relative humidity at Taboga station (10°21', 85°09', 40 m above sea level). The period of analysis is 1976-1984.

Methodology

Here only a summary of the methodology used to calculate the PDI will be presented and for details the reader is referred to Palmer (1965).

In order to calculate the PDI the following steps are made:

- 1) A monthly water balance is made for a relatively long series of years.
- 2) With the results obtained in (1), monthly values of five constants (α , β , γ , δ and K in Palmer's terminology), which define some characteristics of humidity of the local climate, are calculated.
- 3) With four of those constants (α , β , γ , and δ), a re-analysis of the water balance for the period considered in the study is carried out. Then the CAFEC (climatically appropriate for existing conditions) precipitation (P_c) is calculated. The P_c is the theoretical amount of precipitation (P_c) is calculated. The P_c is the theoretical amount of precipitation necessary to maintain the normal levels of evapotranspiration, runoff, and storage of humidity during a specific month.
- 4) An index of moisture anomaly (Z) for each month is calculated by applying a weighting factor to the deviation of humidity (d). This weighting factor is the constant K mentioned in (2). The value of d is the difference between the actual precipitation (P) and the P_c .
- 5) The monthly values (X) of the PDI are obtained from the equation:

$$X_i = X_{i-1} + \frac{Z}{3.0} - 0.103X \quad (1)$$

where the sub-script I refers to a particular month and therefore $i-1$ to the preceding month.

The water balance is carried out month by month from P , potential evapotranspiration (PE), and the available water capacity of the system (AWC) according to the equation

$$P = ET + RO + R - L, \quad (2)$$

where ET is the actual evapotranspiration, RO the runoff, R the total recharge of humidity in the soil, and L the total loss of humidity in the soil.

For computations of the water balance, a model in which the soil is divided into two layers is used. The upper layer is the plow layer and is assumed to contain 2.5 cm of available moisture at field capacity (i.e. the amount of water that a soil retains against gravity when it is allowed to drain freely). In this upper layer the evapotranspiration occurs potentially until all available water has been consumed. The lower layer extends up to the level where the useful soil ends. The availability of water in this layer depends on the depth of the root-system and, therefore, on the types of crops and soil characteristics of the region. Once the available water of the upper layer has been consumed, the water content of the lower layer can be used. This loss depends on the initial humidity content, potential evapotranspiration (PE) and the AWC in the two-layer soil system. It is assumed that there is no recharge of humidity in the lower layer if the upper one is not at its field capacity.

In this study, AWC was taken equal to 125 mm. Previous studies by Herrera (1984), Rojas (1985), and data unpublished by the Costa Rica National Meteorological Institute indicate that a value of 125 mm is representative for the region of study. The dependence of the PDI on AWC is discussed in Section 6.

Palmer calculated the PE using Thornthwaite's method, in which PE is mainly a function of temperature. In the present study, Hargreaves' method was used (Hargreaves, 1974, 1975; Pate, 1976), in which PE is obtained from:

$$PE = 0.0075 (RSM) (TM), \quad (3)$$

where

$$RSM = 0.075 (RMM) (S^{1/2}) \quad (4)$$

$$S = 12.5 (100 - HM)^{1/2} \quad (5)$$

and RSM is the solar radiation (in mm of evaporation per month), TM is the average monthly temperature (in °F), RMM the extraterrestrial radiation (in mm of evaporation per month), S the sunshine (in percent), and HM the relative humidity (in percent).

The monthly values of PE at Liberia station were calculated using several methods (Figure 4). A description of these methods is given by WMO (1966), Ramírez (1976), and Hargreaves (1974, 1975). It can be seen that Hargreaves' method gives intermediate values, which seems convenient for a region lacking confident measurements of the evapotranspiration (ET). Several authors used Hargreaves' method in tropical latitudes with good results, while Thornthwaite's method has not been recommended for tropical regions (e.g., Ramírez, 1976). In this study, Hargreaves' method was chosen because of the availability of data for its computation; for example, it does not require wind data which are scarce for the period considered in this study.

For the computation of hydrologic balance, Palmer assumes that the potential runoff (PRO), which is the maximum runoff that can occur, is equal to the potential precipitation minus the potential amount of moisture that could be added to the soil for zero PE. In other words $PRO = AWC - PR$ where PR is the potential recharge; the potential precipitation being equivalent to AWC. In the present study, for the computation of the PRO the procedure of Thornthwaite and Mather (1957) is followed. They assume that once the requirements of potential evapotranspiration have been carried out, all excess of water could potentially runoff; thus PRO is the RO value when the soil is already at field capacity, i.e. when $R = PR = 0$.

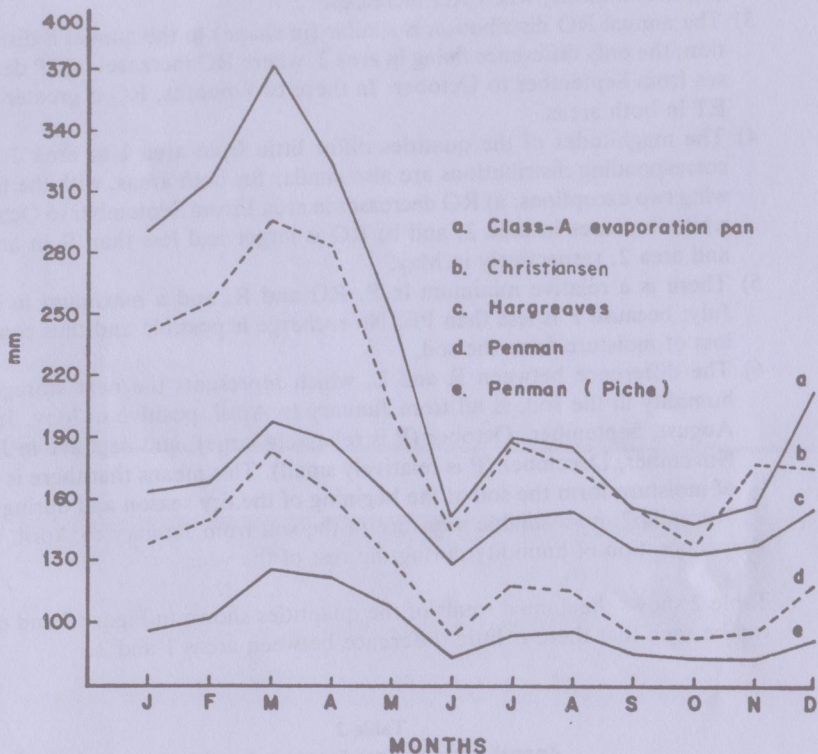


Figure 4. Monthly distributions of potential evapotranspiration at Liberia station (10°37', 85°26', 144 m above sea level), obtained by several methods. The values of evaporation obtained with the class-A pan are also shown. The period of analysis is 1976-1984.

Results

The hydrological balance

Figures 5 and 6 show the average values of the quantities required in (2) for the hydrological balance of areas 1 and 2, respectively. The following points can be deduced from the figures:

- 1) ET is greater or equal to P from November to April (dry season) and in July (veranillo); the difference being quite large in December. In the rest of the months P is much larger than ET.

- 2) ET is the largest term in (2) for all months except September and October (rainiest months) when RO increases.
- 3) The annual RO distribution is similar (in shape) to the annual P distribution; the only difference being in area 2, where RO increases and P decreases from September to October. In these two months, RO is greater than ET in both areas.
- 4) The magnitudes of the quantities differ little from area 1 to area 2. The corresponding distributions are also similar for both areas, with the following two exceptions: a) RO decreases in area 1 from September to October while increases in area 2, and b) RO is larger and less than R in area 1 and area 2, respectively in May.
- 5) There is a relative minimum in P, RO and R, and a maximum in L in July; because P is less than PE. No recharge is possible and thus causing loss of moisture from the soil.
- 6) The difference between R and L, which represents the next storage of humidity in the soil, is nil from January to April, positive in May, June, August, September, October (P is relatively large), and negative in July, November, December (P is relatively small). This means that there is loss of moisture from the soil at the beginning of the dry season and during the "veranillo", no available moisture in the soil from January to April, and recuperation of humidity during the rest of the year.

Table 2 shows the annual totals of the quantities shown in Figure 5 and 6. It can be seen that there is little difference between areas 1 and 2.

Table 2
Annual water balance for areas 1 and 2

| | P | = | ET | + | RO | + | R | - | L |
|---------|-------|---|-------|---|------|---|------|---|------|
| Area 1 | 164.8 | | 107.7 | | 57.6 | | 15.1 | | 15.6 |
| Area 2 | 158.7 | | 105.1 | | 54.2 | | 15.7 | | 16.3 |
| Average | 162.0 | | 106.5 | | 56.0 | | 15.5 | | 16.0 |

PDI values and drought periods

Figure 7 shows the distribution of PDI values for areas 1 and 2, and for the whole region during the 138 month period considered in this paper. From this figure, the drought periods for areas 1 and 2, and the whole region were obtained and are shown in tables 3, 4, and 5, respectively. From these tables the following points can be deduced:

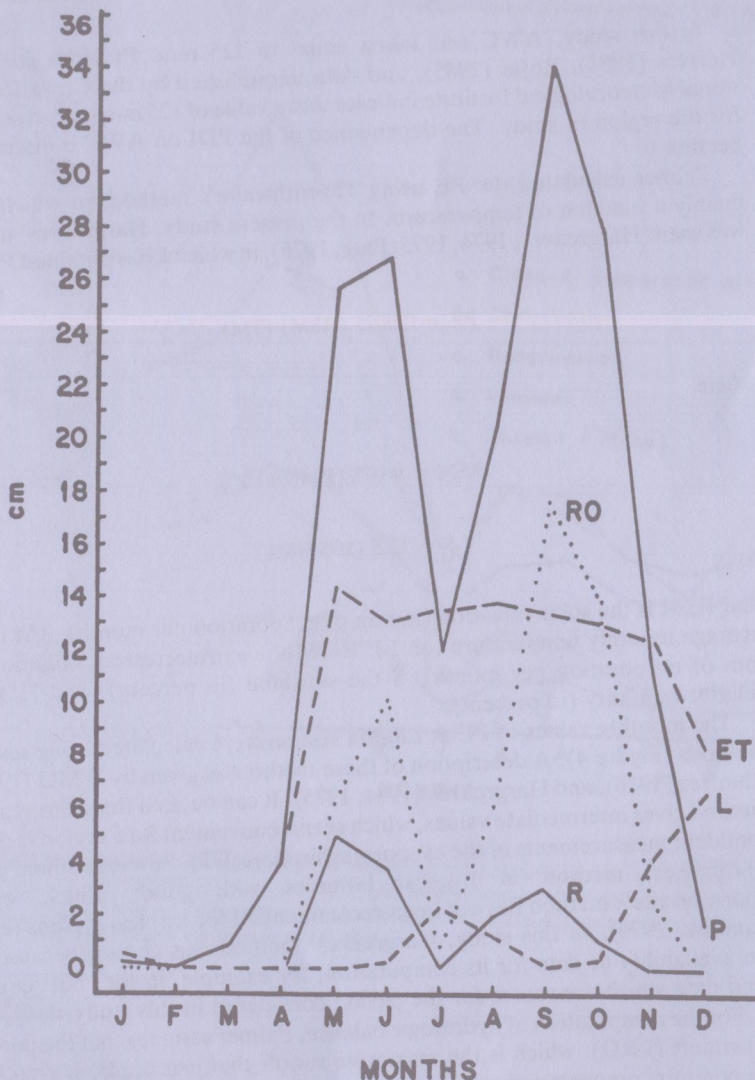


Figure 5. Monthly water balance for area 1 (Equation 2): P (precipitation), ET (evapotranspiration), RO (runoff), R (total recharge of humidity in the soil), and L (total loss of humidity in the soil). The period of analysis is July 1972-December 1983.

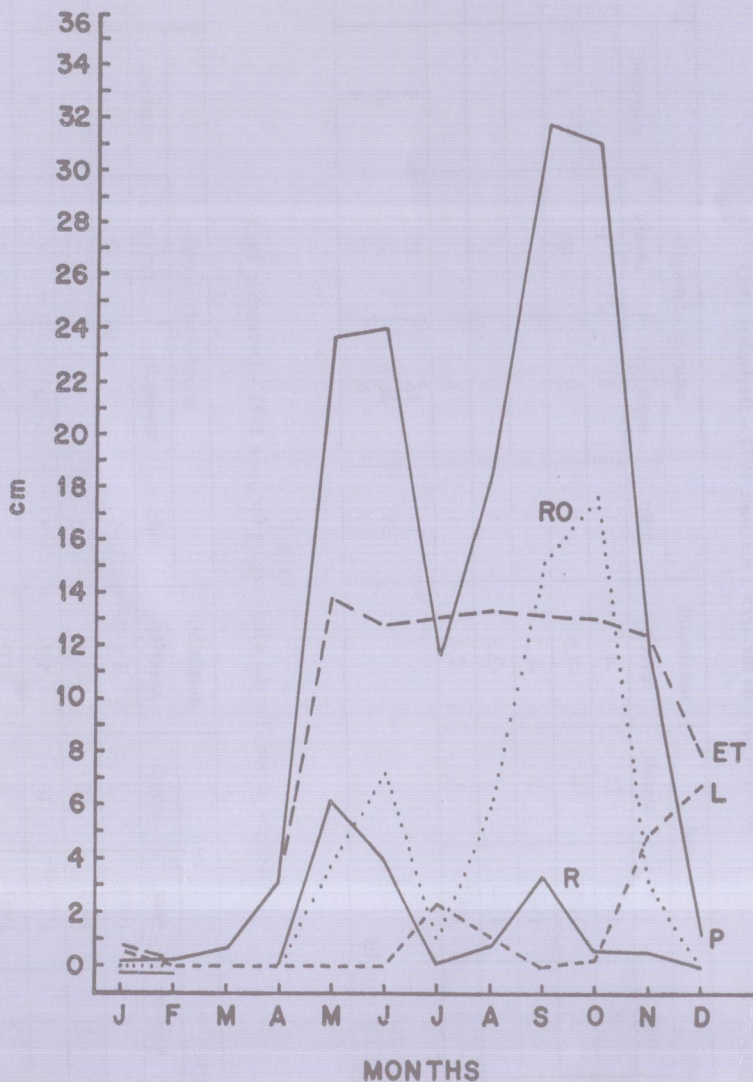


Figure 6. The same as Fig. 5 except for area 2.

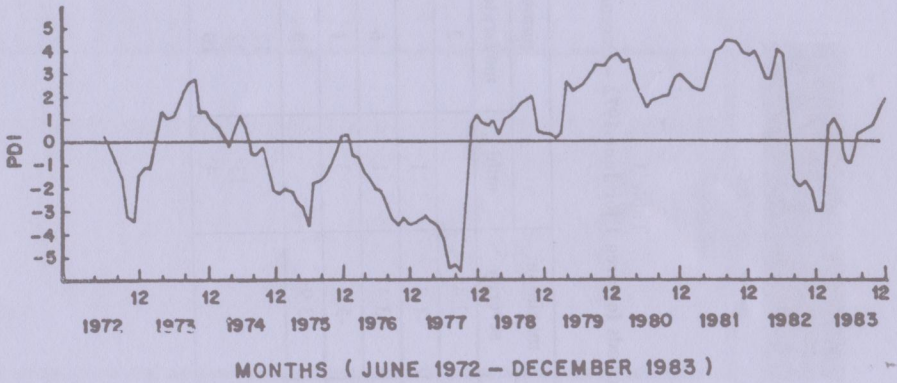
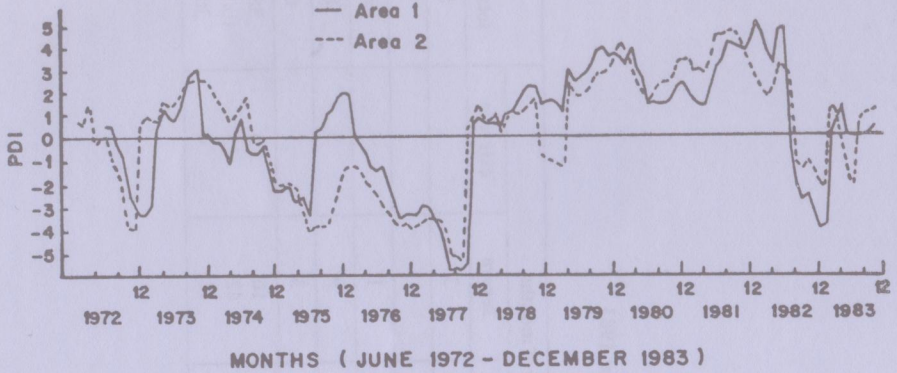


Figure 7. Monthly values of Palmer's Drought Index (PDI). Top diagram: values for area 1 (full line) and 2 (dashed line). Bottom diagram: average values for the whole region of study. The period of analysis is June 1972-December 1983.

- 1) In area 1, 30% of the 130 month period had drought conditions with 4% mild, 10% moderate, 12% severe, and 4% extreme droughts.
- 2) In area 2, 36% of the 138 month period has drought conditions with 10% mild, 9% moderate, 12% severe and 4% extreme droughts.
- 3) In the whole region, 32% of the 138 month period had drought conditions with 7% mild, 11% moderate, 11% severe, and 3% extreme droughts.
- 4) Most of the droughts (75% for the whole region) started in the second half of the year. This way be due to the fact that the "veranillos" in 1972, 1977 and 1982 were quite long and thus acquired drought characteristics (Ramírez, 1983). In general, the largest drought severities were observed during the second half of the year.

Table 3
Drought periods for area 1 for June 1972 - December 1983

| start | | end | | maximum severity | number of months | | | | total |
|--------------------------|-------|------|-------|------------------|------------------|----------|--------|---------|-------|
| year | month | year | month | | mild | moderate | severe | extreme | |
| 1972 | 10 | 1973 | 2 | -3.4 | | 2 | 3 | | 5 |
| 1974 | 4 | 1974 | 4 | -1.2 | 1 | | | | 1 |
| 1974 | 11 | 1975 | 6 | -3.4 | 1 | 6 | 1 | | 8 |
| 1976 | 5 | 1977 | 10 | -5.9 | 3 | 1 | 9 | 5 | 18 |
| 1982 | 8 | 1983 | 1 | -3.9 | | 3 | 3 | | 6 |
| total | | | | | 5 | 12 | 16 | 5 | 38 |
| relative percentage | | | | | 13 | 32 | 42 | 13 | 100 |
| percentage of 138 months | | | | | 4 | 10 | 12 | 4 | 30 |

Table 4
Drought periods for area 2 for June 1972 – December 1983

| start | | | end | | maximum severity | number of months | | | | total |
|--------------------------|-------|------|-------|------|------------------|------------------|--------|---------|----|-------|
| year | month | year | month | mild | | moderate | severe | extreme | | |
| 1972 | 8 | 1972 | 11 | -4.1 | 1 | 1 | 1 | 1 | 4 | |
| 1974 | 12 | 1977 | 9 | -5.5 | 5 | 9 | 16 | 4 | 35 | |
| 1979 | 1 | 1979 | 3 | -1.3 | 3 | | | | 3 | |
| 1982 | 8 | 1983 | 1 | -2.2 | 4 | 2 | | | 6 | |
| 1983 | 5 | 1983 | 6 | -2.1 | 1 | 1 | | | 2 | |
| total | | | | | | | | | | |
| relative percentage | | | | | | 14 | 13 | 17 | 5 | 50 |
| percentage of 138 months | | | | | | 28 | 26 | 34 | 10 | 100 |
| | | | | | | 10 | 9 | 12 | 4 | 36 |

Table 5
Drought periods for the whole region for June 1972 – December 1983

| start | | | end | | maximum severity | number of months | | | | total |
|--------------------------|-------|------|-------|------|------------------|------------------|--------|---------|----|-------|
| year | month | year | month | mild | | moderate | severe | extreme | | |
| 1972 | 8 | 1973 | 2 | -3.5 | 1 | 4 | 2 | | 7 | |
| 1974 | 11 | 1975 | 10 | -3.8 | 5 | 5 | 2 | | 12 | |
| 1976 | 4 | 1977 | 10 | -5.7 | 2 | 4 | 9 | 4 | 19 | |
| 1982 | 8 | 1983 | 1 | -3.0 | 2 | 2 | 2 | | 6 | |
| total | | | | | | | | | | |
| relative percentage | | | | | | 10 | 15 | 15 | 4 | 44 |
| percentage of 138 months | | | | | | 23 | 34 | 34 | 9 | 100 |
| | | | | | | 7 | 11 | 11 | 3 | 32 |

Figure 7 and tables 3 and 4 show that there are some differences between areas 1 and 2 in the severity and dates of occurrence of the droughts. For example, the maximum drought severity in area 1 occurred in December 1972 – January 1973, while in area 2 in November 1972. In the second half of 1975, area 1 showed drought conditions and area 2 did not, while the contrary occurred from January to March of 1979. This means that under the same general synoptic patterns, drought conditions can change from place to place within a relatively small region. It can be observed from Figure 7 that in area 1 a long humid period, say from November 1977 to June 1982, followed the extreme drought conditions of 1977. This also holds true for area 2, with the exception that a mild drought occurred in the first three months of 1979.

Areal distribution of PDI – Drought of 1977

The drought that attained its maximum severity in 1977 (called the drought of 1977) had a duration of 18 months in area 1 (from May 1976 to October 1977) and 35 months in area 2 (from December 1974 to September 1977). This was the most intense drought observed in the period of analysis (Figure 7).

Table 6 shows PDI values, at the meteorological stations shown in Figure 1, for the two months (July and September, 1977) in which the drought was more severe. It can be inferred that the least affected zone is the northeastern central part of the region of study (Bagaces station) and that the most affected zones are the northwestern and southeastern parts of the region.

Table 6
PDI values for two particular months

| Station | July 1977 | September 1977 |
|--------------|-----------|----------------|
| Liberia | -5.6 | -5.0 |
| Bagaces | -0.8 | -2.3 |
| H. Tempisque | -4.2 | -5.1 |
| Cañas | -4.1 | -4.9 |
| Taboga | -5.3 | -5.3 |

Comparison of the results with observations

Herrera (1984) compiled information from the press about damage caused by severe storms, floods, and droughts in different regions of Costa Rica. According to this information, crop damage caused by droughts occurred in the region of study in the periods indicated in Table 7. These periods agree with the PDI values shown in Figure 7. However, some months of drought or of high humidity (Figure 7) were not reported in the press. This may be due to the fact that the drought could have affected the region of study at

times when the drought conditions were not so adverse for the crops, or the region affected was relatively small and, therefore, no serious agricultural damage was reported. For example, examining the PDI values of Figure 7 for September 1975 – January 1976 especially those of September 1975 and January 1976, it can be seen that humidity prevailed in area 1 whereas drought conditions predominated in areas 2.

It should be re-emphasised here that the PDI is based on the meteorological conditions of the region. Therefore, reports about crop damage area only indicative of the reliability of Palmer's method in those regions and at those times of the year in which agricultural practices are carried out.

In general, a careful analysis of all the information compiled from the press by Herrera (1984) shows that all reports of crop damage agree with a drought or an anormal humid period as determined from the PDI values of Figure 7. For example, all the crop damage of 1980 and 1981 was reported to be caused by heavy rains. The PDI values for these years indicate excessively humid conditions (Figure 7).

Table 7

Periods in which drought conditions occurred according to the reports from the press about crop damage compiled by Herrera (1984)

| Year | Month |
|------|-------------------|
| 1972 | August, September |
| 1973 | March |
| 1976 | September |
| 1977 | August |
| 1982 | August, September |

Dependence of Palmer's drought index on the available water capacity of the soil system and the potential evapotranspiration

PDI values were computed for different values of AWC for every month and for several years. Figure 8 shows two examples for the results. A simple functional relationship between PDI and AWC is not observed as expected. However, the computations show that an error in the estimation of AWC of about 50% with respect to the value of 125 mm used in this study would not have significantly changed the results.

Similar computations were also carried out to examine the dependence of PDI on the PE values obtained from four different methods (Figure 9). It was found that the differences between the PDI values obtained by the different methods of computing PE are, in general, small. In the case of 1977, it is observed that the differences are very small from January to July and comparatively larger from August to December (Figure 9); the drought being more severe during the second half of 1977 (Figure 7).

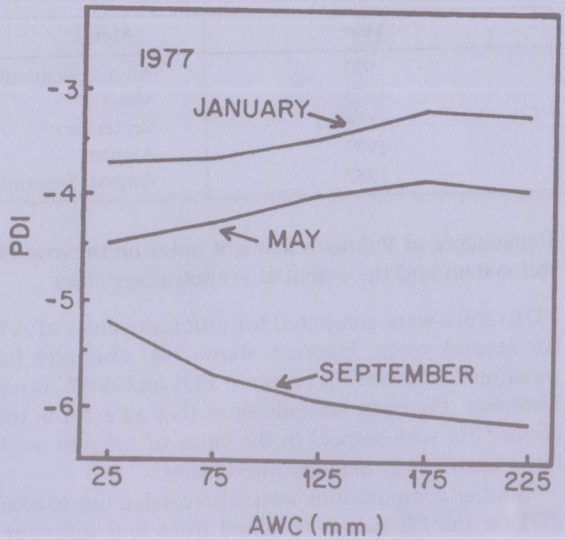
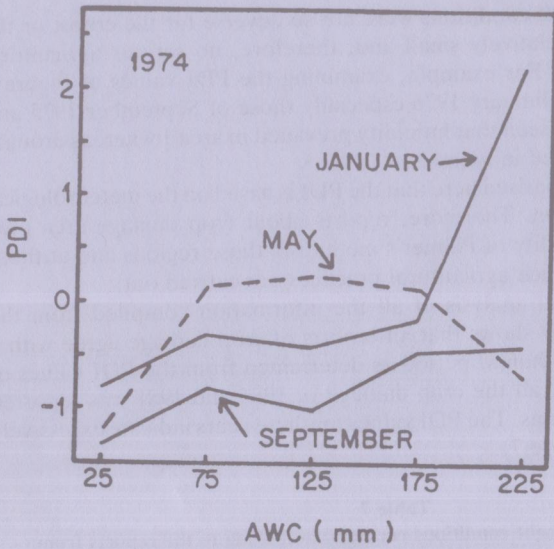


Figure 8. Variation of PDI versus the available water capacity of the soil system (AWC) in area 1 for January, May, and September of 1974 (left side) and 1977 (right side).

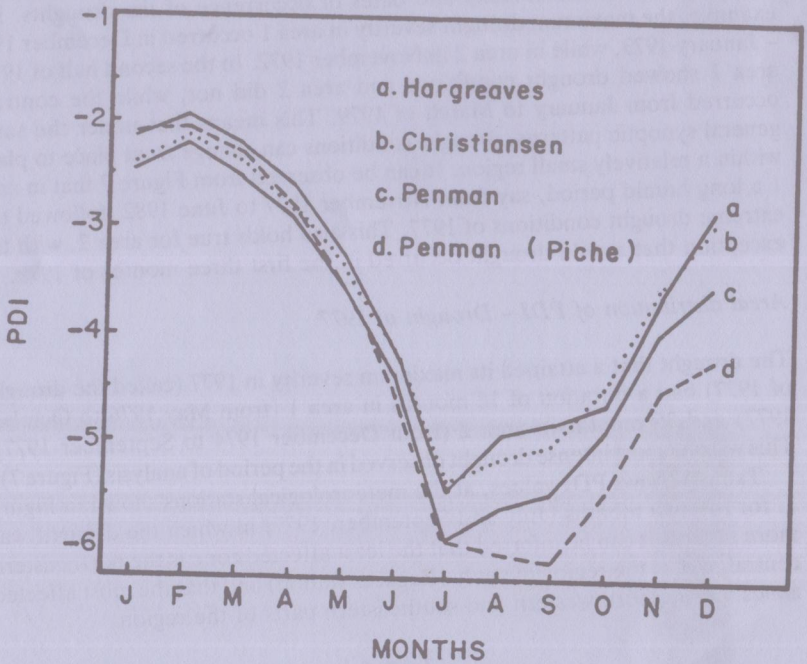


Figure 9. Monthly distribution of PDI at Liberia station for 1977 for four methods of computing potential evapotranspiration.

Summary and conclusions

In this paper the PDI was applied to a semi-arid region in Costa Rica, which was divided into two areas (Figure 1). The period of analysis was June 1972 to December 1983 (i.e. 138 months).

The PDI values show that area 1 had fewer months of drought than area 2. In area 1, 30% of the 138 month period experienced drought conditions, with 4% mild, 10% moderate, 12% severe, and 4% extreme droughts (according to Palmer's classification). In area 2, 36% of the 138 month period experienced drought conditions, with 10% mild, 9% moderate, 12% severe, and 4% extreme droughts. Any tendency for droughts to start or end in a particular month was not found; although most of the severe droughts occurred in the second half of the year.

For the whole region, it was found that 32% of the 138 month period showed drought conditions, with 7% mild, 11% moderate, 11% severe, and 3% extreme droughts. Four droughts in 1972, 1974, 1976, and 1982, with a minimum duration of four months, affected the whole region. The drought

that started in 1976 had the longest duration (19 months); it attained its maximum severity in 1977. The areal distribution of the PDI for July and September, 1977 showed that the least affected zone was the northeastern central part of the region and that the most affected were the northwestern and southeastern parts.

The PDI values were compared with reports from the press about crop damage and very good agreement was found.

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References

- Hargreaves, G.H., 1974. *Climate and moisture availability for Costa Rica*. Utah State University, Logan, Utah, U.S.A.
- Hargreaves, G.H., 1975. *Water requirements manual for irrigated crops and rainfed agriculture*. Utah State University, Logan, Utah, U.S.A., 40 pp.
- Herrera, H., 1984. *Evaluación del estado de los cultivos por medio de técnicas agrometeorológicas*. Informe final del proyecto auspiciado bajo el convenio NOAA/AID PASA BOF-0000-P-CC-3062-02 y subsidio de NOAA No. 84-AAH-00074 (available from: Instituto Meteorológico Nacional, Apartado 7-3350, San José, Costa Rica), 100 pp.
- Palmer, W.C., 1965. *Meteorological drought*. Research paper No. 45, U.S. weather Bureau, Washington D.C., U.S.A., 58 pp.
- Pate, A.J., 1976. *Validity of evapotranspiration prediction in Costa Rica*. Utah State University, Logan Utah, U.S.A., 17 pp.
- Ramírez, P., 1976. *Cálculo de la evaporación y evapotranspiración en Costa Rica*. Tesis de Licenciatura, Universidad de Costa Rica, San José, Costa Rica, 104 pp.
- Ramírez, P., 1983. *Estudio meteorológico de los veranillos en Costa Rica*. Nota de investigación No. 5, Instituto Meteorológico Nacional, San José, Costa Rica, 47 pp.
- Rojas, O., 1985. *Estudio de las condiciones hídricas del Pacífico Norte de Costa Rica*. Serie de Publicaciones Misceláneas No. 546, Instituto Interamericano de Cooperación par la Agricultura (IICA), San José, Costa Rica, 73 pp.

- Thornthwaite, C.W., and Mather, J.R., 1975. "Instruction and tables for computing potential evapotranspiration and the water balance". *Climatology Publications*, Vol. 10, No.3, Drexel Institute of Technology, Centerton, New Jersey, U.S.A., 311 pp.
- WMO, 1966. *Measurement and estimation of evaporation and evapotranspiration*. WMO No. 201. TP. 105, World Meteorological Organization, Geneva, Suisse, 121 pp.