






CLIMATOLOGICAL WATER BALANCE AND CLIMATE CLASSIFICATION OF THORNTHWAITE AND MATHER FOR BENIN, WEST AFRICA, IN 1970-2015 PERIOD

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ABSTRACT

The climate is described by the predominant atmospheric conditions in a particular region and influences several human activities. In agriculture, water availability defines the growth and yield of crops and can be obtained by the water balance. The climate classification also aids to identify suitable areas for agricultural crops. Thus, the aim of this work was to elaborate the water balance and perform the climate classification through the method of Thornthwaite and Mather (1955) for six weather stations (Bohicon, Cotonou-Airport, Kandi-Airport, Natitingou, Parakou-Airport and Savè) located in Benin, Western Africa. For the execution of this work, monthly series of precipitation and potential evapotranspiration from 1970 to 2015 were used. Once the monthly water balance of the six seasons was elaborated, it was observed that the rainy (dry) period decreases (increases) from the coast (Cotonou-Airport) to the north of Benin (Kandi-Airport) and, coincides with Boreal summer and part of autumn (Boreal winter and part of spring). Regarding the climate classification, the Cotonou-Airport station was characterized as Subhumid Megathermal climate with moderate winter deficit ($C_2wA'a'$); the stations of Bohicon and Savè presented similar climate classification with Subhumid Dry Megathermal climate with low or without water surplus ($C_1dA'a'$); Natitingou with Subhumid Dry climate Megathermal with large summer surplus ($C_1s_2A'a'$); Parakou-Airport with Subhumid climate Dry Megathermic with moderate summer surplus ($C_1sA'a'$) and, Kandi-Airport presented Semi-arid Megathermal climate with moderate summer surplus ($DsA'a'$). In Benin, subsistence and rainfed farming showed greater risk in the north of the country due to the decrease in the rainy season and the water surplus from the coast (south) to the north of the country, with the increase in aridity.

Palavras-chave:

Evapotranspiração
Chuva
Deficiência hídrica
Excedente hídrico

BALANÇO HÍDRICO CLIMATOLÓGICO E CLASSIFICAÇÃO CLIMÁTICA DE THORNTHWAITE E MATHER PARA O BENIM, ÁFRICA OCIDENTAL, NO PERÍODO DE 1970-2015

RESUMO

O padrão climático é descrito pelas condições atmosféricas predominantes de determinada região e, influencia diversas atividades humanas. Na agricultura, a disponibilidade hídrica define o crescimento e produtividade das culturas e, pode ser obtida pelo balanço hídrico. A classificação climática auxilia também na identificação de zonas aptas aos cultivos agrícolas. Assim, o objetivo deste trabalho foi elaborar o balanço hídrico e realizar a classificação climática pelo método de Thornthwaite e Mather (1955) para seis estações meteorológicas (Bohicon, Cotonou-Aeroporto, Kandi-Aeroporto, Natitingou, Parakou-Aeroporto e Savè) localizadas no Benim, África Ocidental. Para a realização do trabalho, foram utilizadas séries mensais de precipitação e evapotranspiração potencial entre os anos de 1970 a 2015. Após a elaboração do balanço hídrico mensal das seis estações, observou-se que o período chuvoso (seco) diminui (aumenta) do litoral (Cotonou-Aeroporto) para o norte do Benim (Kandi-Aeroporto) e, coincide com o verão Boreal e parte do outono (inverno Boreal e parte da primavera). Com relação à classificação climática, a estação de Cotonou-Aeroporto foi caracterizado como clima Subúmido Megatérmico com moderada deficiência de inverno ($C_2wA'a'$), as estações de Bohicon e Savè apresentaram classificação climática semelhantes com clima Subúmido Seco Megatérmico com excedente hídrico pequeno ou nulo ($C_1dA'a'$), Natitingou com clima Subúmido Seco, Megatérmico com elevado excedente de verão ($C_1s_2A'a'$), Parakou-Aeroporto com clima Subúmido Seco Megatérmico com moderado excedente de verão ($C_1sA'a'$) e Kandi-Aeroporto apresentou clima Semiárido, Megatérmico com moderado excedente de verão ($DsA'a'$). No Benim, a atividade agrícola de subsistência e em regime de sequeiro apresenta maior risco no norte do País, devido a diminuição do período chuvoso e do excedente hídrico do litoral (sul) em direção ao norte, com o aumento da aridez.

INTRODUCTION

The climate is the set of average atmospheric conditions that characterize a region (JYLHÄ *et al.*, 2010). The study of climate is of great importance for several applications in the biosphere (ENGELBRECHT *et al.*, 2016), in which the water balance and climate classification are the major tools to synthesize the climatic characteristics of a given location (MARTINS *et al.*, 2018). According to Medeiros *et al.* (2013), it is not possible to characterize a climate as wet or dry based only on precipitation data. It is necessary to know whether the precipitation is greater or less than the water required for evapotranspiration, which makes precipitation and evapotranspiration important climatic factors.

Assessment of the agroclimatic patterns of a particular location is the primary step in agricultural planning. Passos *et al.* (2016) state that the estimation of the climatological water balance (CWB) and the climatic classification are essential agroclimatic tools in determining suitability zones for crops and in design of irrigation systems. Through the CWB, the planning and management of soil and water can be carried out, determining, for example, the water requirement for water for crops (COUTINHO *et al.*, 2015; MATOS *et al.*, 2014; PEREIRA *et al.*, 2002). Based on the components of the CWB, it is still possible to define the period of growth, rainy and dry season (FRERE; POPOV, 1979) and thus establish a calendar of plating, harvesting and other cultural practices and agroclimatic zoning (COUTINHO *et al.*, 2015; ROLIM *et al.*, 2007; PEREIRA *et al.*, 2002)

The CWB is one of several ways of monitoring soil water storage, from which the deficiency (DEF) and water surplus (SUR), the replacement and removal of water from the soil, and the actual evapotranspiration (ET_a) are determined. The components of the CWB are still used to carry out the climate classification (ROLIM *et al.*, 2007; JESUS, 2015; PEREIRA *et al.*, 2002). There are several climatic classification systems, especially

the one proposed by Thornthwaite and Mather (1955), which uses indexes defined based on the CWB (SILVA *et al.*, 2014). Rolim *et al.* (2007) claim that Thornthwaite and Mather's classification is indicated to support agricultural activities, as it is sensitive to macro and mesoclimatic factors (topoclimatic), while Köppen's classification is influenced by macroclimatic factors.

According to Adjovi *et al.* (2018), because of its basic fomenting function and its multifunctional nature, the agricultural sector is included in several sustainable development objectives, which include food security. Agriculture is a vital sector in African countries, which concentrates between 25 and 35% of direct jobs, depending on the country, and contributes to the income of almost 70% of the African population. Despite its importance, farming is extremely vulnerable to the effects of climate, particularly in West African countries, as it is mostly carried out in a rainfed regime, with a low aggregated technological level, associated with the occurrence of extreme climatic conditions (e.g., droughts, floods, heat waves) and a trend towards a decreasing availability of water resources in the region.

Developing countries in West Africa, including Benin, are particularly vulnerable to adverse climate effects due to their high dependence on natural resources and low adaptive capacity (ADJOVI *et al.*, 2018). In Benin, this is partly a result of the significant deficit of water resources, which deprives this population of access to water (AMOUSSOU *et al.*, 2016). In addition to the deficit, the irregularity of rainfall distribution observed in the last decades in Benin represents challenges for agricultural production (DJOHY *et al.*, 2015).

Thus, due to the restriction of recent studies based on the CWB and the climate classification by Thornthwaite and Mather (1955), the climate characterization of Benin becomes crucial for better planning of agricultural activities and reducing the risk of subsistence agriculture in this Country. Therefore, the aim of this work was to elaborate the climatological water balance and the

Thornthwaite and Mather climate classification for Benin in the period 1970-2015. Based on the climatological water balance, dry and rainy season will be identified to support water and agriculture management in Benin. The first step will be to evaluate the seasonal variability of rainfall and evapotranspiration in Benin based on the climatological water balance and then carry out the climatic classification, using the method of Thornthwaite and Mather (1955).

MATERIAL AND METHODS

Study area characterization

Benin is located in West Africa, in the tropical zone between the Equator and the Tropic of Cancer (between the 6°30' and 12°30' N parallels and the 1°00' and 3°40' E meridians). The country has a total area of approximately 114,763 km², being limited to the north by the Niger River, which separates it from the Republic of Niger; on the northwest by Burkina Faso, on the west by Togo, on

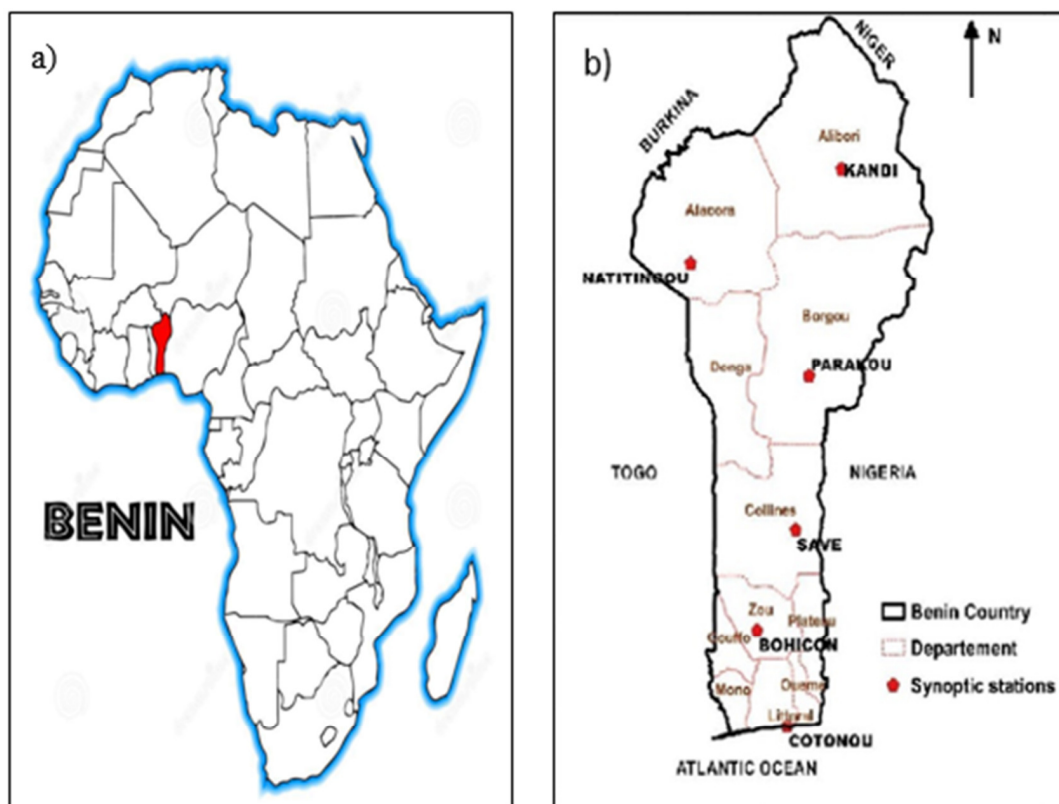
the east by Nigeria, and on the south by the Atlantic Ocean. The average maximum air temperatures in the country vary between 28 and 33.5°C, while the average minimums fluctuate between 24.5 and 27.5°C (BIAOU *et al.*, 2014).

Figure 1 shows the location of Benin and the spatial distribution of the meteorological stations used in Benin.

According to DJOSSA *et al.* (2015), The relief of Benin, little rugged, consists of a sandy coastal strip followed by two areas of plateaus and the Atacora massif to the north from which all the rivers are born.

Weather Stations

For the execution of this work, monthly average data of the rainfall and potential evapotranspiration (PET) were used. The data covered the period from 1970 to 2015, totaling 45 years, six weather stations of the Benin National Climate Institute (Météo-Bénin) (Table 1).



Source: OBADA *et al.* (2017) and DJOSSA *et al.* (2015)

Figure 1. Location of a) Benin in West Africa and b) spatial distribution of the weather stations used in this work.

Table 1. Pre-selected weather stations of Benin

N°	Name of the stations	Latitude	Longitude	Altitude	OMM Code (WMO)
1	Bohicon	2°07E	7°17N	167 m	65338
2	Cotonou-Airport	2°38E	6°35N	9 m	65344
3	Kandi-Airport	2°93E	11°13N	292 m	65306
4	Natitingou	1°38E	10°32N	461 m	65319
5	Parakou-Airport	2°62E	9°35N	393 m	65330
6	Savè	2°47E	8°03N	200 m	65335

Climatic Water Balance (CWB)

The climatic water balance (CWB) was obtained using the method proposed by Thornthwaite and Mather (1955), using an electronic spreadsheet developed by Rolim *et al.* (1998). In the calculation of the CWB, the value of 100 mm was adopted for the available soil water capacity (ASWC).

Based on the data obtained at the CWB, the actual evapotranspiration (ETa), monthly water deficit (DEF), and water surplus (SUR) were determined and the climatic classification was carried out following the method of Thornthwaite and Mather (1955). This climate classification is based on the values of the water index (Ih), aridity index (Ia), and the moisture index (Iu), obtained through Equations 1 - 3:

$$Ih = \frac{SUR}{PET} \times 100 \tag{1}$$

$$Ia = \frac{DEF}{PET} \times 100 \tag{2}$$

$$Iu = Ih - 0.6Ia \tag{3}$$

in which:

Ih = water index;

Ia = aridity index;

Iu = moisture index;

DEF = water deficit, in mm;

SUR = water surplus, in mm;

PET = potential evapotranspiration, in mm.

Climatic classification following the methodology of Thornthwaite and Mather (1955)

This climate classification uses four respective

$$\alpha = 6.75 \cdot 10^{-7} I^3 - 7.71 \cdot 10^{-5} I^2 + 1.7912 \cdot 10^{-2} I + 0.49239 \tag{5}$$

keys to determine the letters that characterize the climate type. Thus, Table 2 shows the initial keys of the climatic classification according to Thornthwaite, based on the moisture indices.

The second letter of the formula, whether upper or lower case with or without subscript (Table 3), indicates the climatic subtype, differentiating the humidity period from the aridity, which occurs during the year as a function of the interannual rainfall distribution.

According to Holanda and Medeiros (2018), to determine the third letter of the climate formula, the thermal efficiency index is necessary. This index corresponds to the numerical value of potential evapotranspiration, being the direct function of temperature and photoperiod. It is presented by a capital letter with an apostrophe and, with or without a subscript digit (Table 4).

Potential evapotranspiration (PET) according to Thornthwaite (1948)

According to Primo *et al.* (2019), the set of equations developed by Thornthwaite (1948) was based on the water balance of hydrographic basins and evapotranspiration measurements carried out in lysimeters and uses only the air temperature as an independent variable. The standard monthly mean potential evapotranspiration (PETp, mm. month) for a 30-day month, and each day with a 12-hour photoperiod, was well represented by the set of equations 4 - 6:

$$PET = 16 \left(10 \frac{Ti}{I} \right)^\alpha \tag{4}$$

$Ti > 0^\circ C$

Table 2. Initial keys of the climatic classification according to Thornthwaite, based on the moisture indices

Climate Types	Moisture Index (Iu)
A – Very humid	$100 \leq Iu$
B' ₄ – Very humid	$80 \leq Iu < 100$
B' ₃ – Humid	$60 \leq Iu < 80$
B' ₂ – Humid	$40 \leq Iu < 60$
B' ₁ – Humid	$20 \leq Iu < 40$
C ₂ – Subhumid	$00 \leq Iu < 20$
C ₁ – Subhumid dry	$20 \leq Iu < 00$
D – Dry	$-40 \leq Iu < -20$
E – Arid	$-60 \leq Iu < -40$

Source: Aparecido et al. (2016)

Table 3. Second key of the climatic classification according to Thornthwaite, based on the aridity and moisture indices

Humid climates (A, B ₄ , B ₃ , B ₂ , B ₁ e C ₂)	Aridity index (Ia)	Dry climates (C ₁ , D e E)	Moisture index (Iu)
r – Without or with low deficit	$0 \leq Ia < 16.7$	d – Without or with low surplus	$0 \leq Iu < 10$
s – Moderate summer deficit	$16.7 \leq Ia < 33.3$	s – Moderate winter surplus	$10 \leq Iu < 20$
w – Moderate winter deficit	$16.7 \leq Ia < 33.3$	w – Moderate Summer surplus	$10 \leq Iu < 20$
s ₂ – Large summer deficit	$Ia \geq 33.3$	s ₂ – Large Summer surplus	$Iu \geq 33.3$
w ₂ – Large winter deficit	$Ia \geq 33.3$	w ₂ – Large winter surplus	$Iu \geq 33.3$

Source: Aparecido et al. (2016)

Table 4. Third letter of the climate according to Thornthwaite, based on the thermal index (PET_{annual})

Climate type	Thermal index (PET _{annual})
A' – Megathermal	$PETa \geq 1.140$
B' ₄ – Mesothermal	$1140 > PETa \geq 997$
B' ₃ – Mesothermal	$997 > PETa \geq 885$
B' ₂ – Mesothermal	$885 > PETa \geq 712$
B' ₁ – Mesothermal	$712 > PETa \geq 570$
C' ₂ – Microthermal	$570 > PETa \geq 427$
C' ₁ – Microthermal	$427 > PETa \geq 285$
D – Tundra	$285 > PETa \geq 142$
E' – Perpetual ice	$PETa < 142$

Source: Aparecido et al. (2016)

$$I = \sum_{i=1}^{12} (0.2 T_i)^{1.514} \quad T_i > 0^\circ C \quad (6)$$

in which:

I= annual index, which corresponds to the sum of the 12-Ti monthly i indices;

Ti = Monthly average air temperature (°C);

a = exponent of the annual index function.

The subscript i represents the month (i.e., i =1, January; i = 2, February, ..., i=12, December).

I represent the heat index of the region and must be calculated using normal values (climatological average). According to Camargo (1966), the months in which the monthly average temperature is below 0°C should not be included in the calculation of I.

For the determination of the fourth letter of the formula, the percentage of potential evapotranspiration that occurs in the summer is considered, providing the climatic subtype (Table 5). It is indicated by a lowercase letter with an apostrophe and, with or without a subscripted digit.

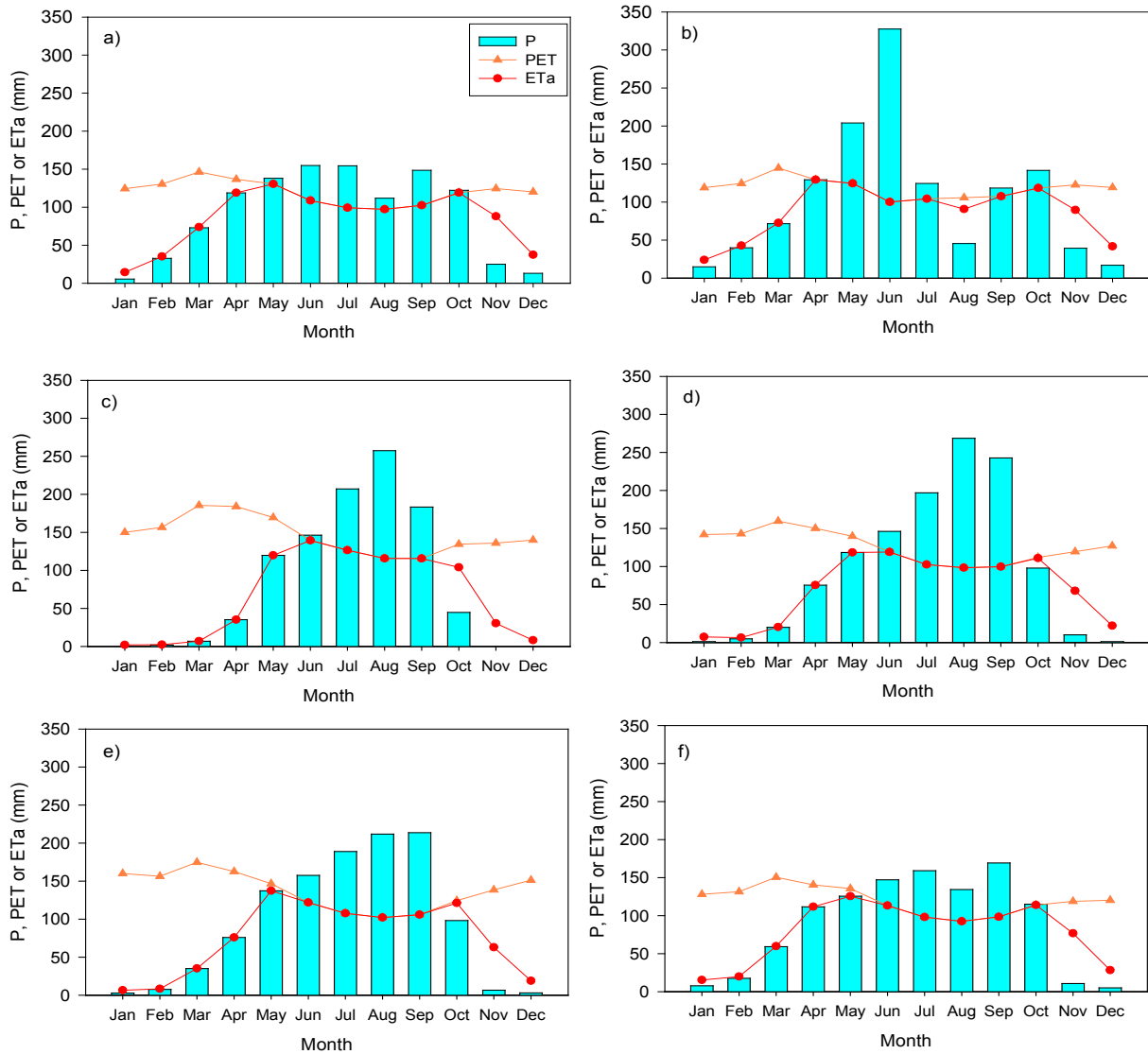


Figure 2. Monthly variation in precipitation (P), potential evapotranspiration (PET), and actual evapotranspiration (ETa) at the weather stations Bohicon (a), Cotonou-Airport (b), Kandi-Airport (c), Natitingou (d), Parakou-Airport (e) and Savè (f) in the 1970-2015 period

Table 5. Forth climatic classification key according to Thornthwaite, based on the relationship between summer PET (PETs) and annual PET

Climate subtype	PETs concentration (%)
a'	PETs < 48%
b' ₄	48 ≤ PETs < 51.9
b' ₃	51.9 ≤ PETs < 56.3
b' ₂	56.3 ≤ PETs < 61.6
b' ₁	61.6 ≤ PETs < 68.0
c' ₂	68.0 ≤ PETs < 76.3
c' ₁	76.3 ≤ PETs < 88.0
d'	88.00 ≤ PETs

Source: Aparecido et al. (2016)

RESULTS AND DISCUSSION

Seasonal variation in rainfall and evapotranspiration in Benin

The results obtained in the variation of the components of the average water balance of the six different stations are shown in Figure 2 (a-f), where the monthly variation of precipitation (P), potential evapotranspiration (PET), and actual evapotranspiration (ETa) considering the period from 1970-2015 is presented.

The total annual precipitation (P) ranged from 1003 mm in Kandi-Airport, in northern Benin, to 1274 mm, in Cotonou-Airport, on the coast. The exception to the pattern of P decrease from the coast to the north of the country was observed in the stations of Parakou-Airport and, mainly in Natitingou, in the north of the country. In these stations, P was higher than that observed in Bohicon and Savè, in the south-central part of the country. Natitingou and Parakou-Airport are located at altitudes above 390 m.a.s.l., and orographic systems may have contributed to this result. The lowest monthly P occurred in January in most stations and December in Savè, with totals between 0.0 mm (Kandi-Airport) and 14.9 mm (Cotonou-Airport), while the highest was observed in June (Bohicon and Cotonou-Airport), August (Kandi-Airport and Natitingou), and September (Parakou-Airport and Savè) and, from 154.8 mm (Bohicon) to 325.7 mm (Cotonou-Airport) (Figure 2).

The annual precipitation observed in this study are within the range of those reported by (YABI *et al.*, 2012) and between 700 and 1,300 mm of annual rainfall distributed over 70 to 110 days in the year. The rainfall pattern in Benin is controlled by the movement of the tropical rain belt known as the Intertropical Convergence Zone (ITCZ), which fluctuates around the equator throughout the year. In northern Benin, there is only one rainy season between May and November, when the ITCZ is in its northernmost position and the southwestern wind prevails; and a dry season from December to March, when the "Harmattan" wind flows from the northeast (McSweeney *et al.*, 2010).

The annual potential evapotranspiration (PET) showed an increasing trend from the coast to the interior of the continent, at the north of the country, with the lowest annual totals (< 1450 mm) observed in Cotonou-Airport, Bohicon, and Savè, while the highest (> 1600 mm) were observed in Kandi-Airport and Parakou-Airport. The monthly

PET variation pattern was inverse to P, with lower PET values (between 92.6 mm – Savè and 115.6 mm – Kandi-Airport) in the Boreal summer (June – Cotonou-Airport, and August – Bohicon, Kandi-Airport, Natitingou, Parakou-Airport, and Savè) and the highest (between 146.3 mm – Bohicon and 185.5 mm – Kandi-Airport) in March, Boreal autumn.

The PET pattern is the result of the proximity of Benin to the Equator, which results in a low amplitude of extraterrestrial solar radiation throughout the year, associated with higher (lower) total rainfall and cloudiness in the summer and part of the autumn (winter and part of the spring), which induce the lower (greater) global solar radiation and, thus, lower (higher) PET values are expected in the summer/rainy (winter/dry) months.

All the stations in this study showed a negative annual P-PET, with an increment pattern of differences from the coast (Cotonou-Airport) to the north (Kandi-Airport) of Benin. The exception was Natitingou, with minor differences in relation to Bohicon, Savè, and Parakou-Airport. The dry season, characterized by months with $(P-PET) < 0$, ranged from eight months in Kandi-Airport, Natitingou, and Parakou-Airport (from October to May), seven months in Savè (from November to May) and Cotonou-Airport (from November to April and August) and six months in Bohicon (November to April). The other months are characterized as the rainy season (FRERE; POPOV, 1979). Similar results were observed by Agbadjagan (2009) which found that the potential water balance (P-PET) was negative in almost all stations.

By definition, PET and ETa had equal values in the rainy season ($P-PET > 0$) and, consequently, no deficit was observed, being ETa lower than PET in the dry season ($P-PET < 0$). In the annual total, ETa ranged from 806 mm (Kandi-Airport) to 1045 mm (Cotonou-Airport), which represented, respectively, a decrease between 26.4 and 54.0% in relation to PET. The ETa seasonal variation pattern showed the highest values between April and October (rainy season), depending on the season, and the lowest in the dry/winter season. The largest differences (> 65 %) between PET and ETa were observed between December and February, extending until March in Natitingou and Parakou-Airport and April in Kandi-Airport.

The PET results are in agreement with those shown by Ogouwale (2015), who found, over the 1971-

2013 period, the highest monthly PET averages between November and May, except for January, with a monthly maximum in March. From June to October, a period of lower temperatures, PET was lower, with a monthly minimum in August and September. As for ETa, the highest values were obtained during the rainy season (April to November), while the dry season was marked by low values, due to the water deficit. The author observed that from November to August, P-PET was negative, thus corresponding to the dry months. From May to July and from September to October, P-PET was positive.

Similar patterns were also found by Müller *et al.* (2018) who observed that in the coastal belts of Benin the annual ETa was close to or equal to 1300

mm year⁻¹ PET, showing that, in general, there is no soil water restriction. This value was lower than that observed for stations near the coast in this study. In the transition between the southern and northern regions of the 15° N parallel, which characterizes the Sahel belt, the authors observed an annual ETa between 300 and 500 mm, demonstrating the reduction in soil water availability in the region near the Equator towards the 20° N parallel was similar to the present study; however, with lower annual totals of ETa.

The results obtained at the CWB are shown in Figure 3 (a-f), where there was a water surplus (SUR) and water deficit (DEF) considering the 1970-2015 period.

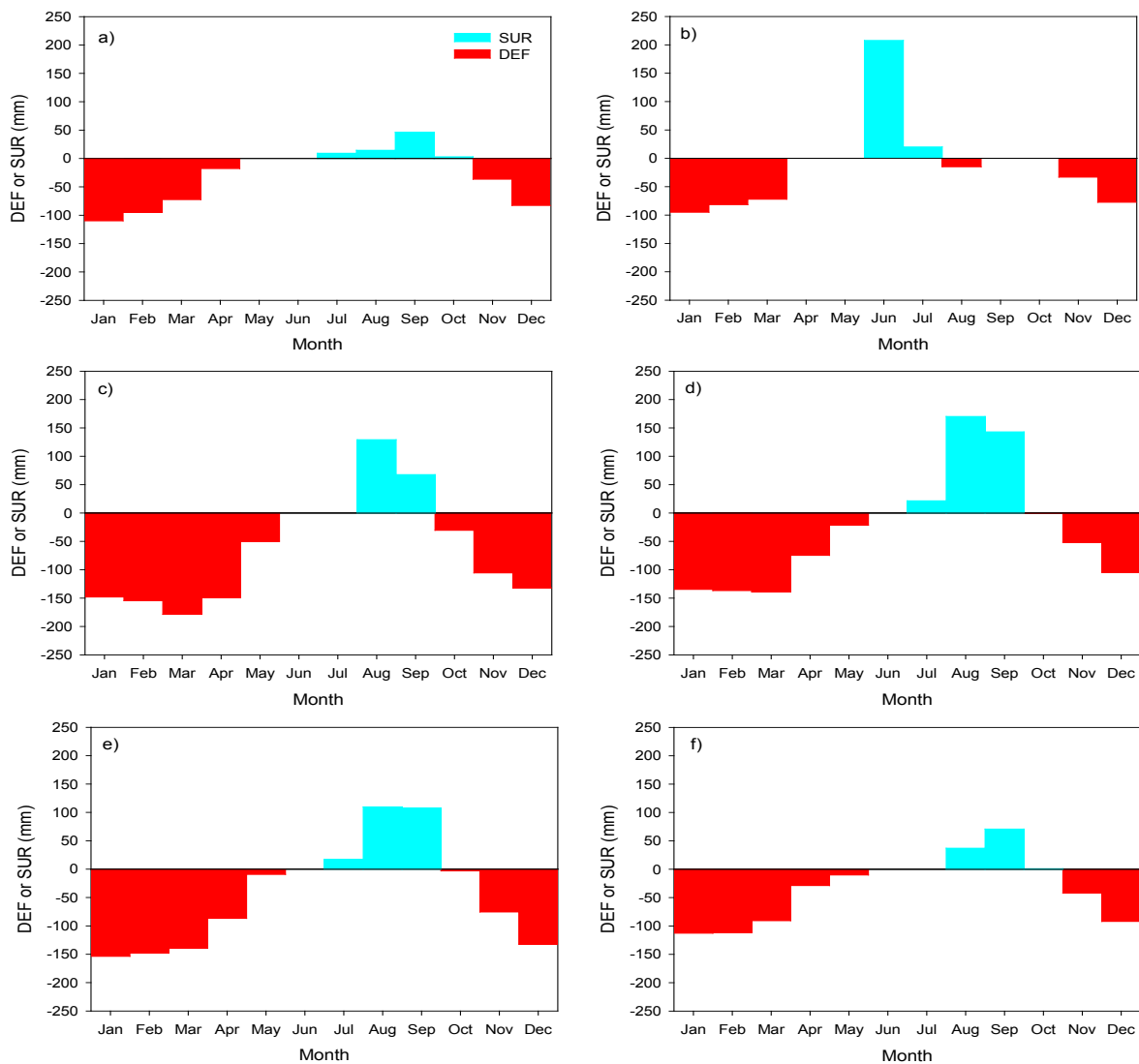


Figure 3. Water deficit (DEF) and water surplus (SUR) at Bohicon (a), Cotonou-Airport (b), Kandi-Airport (c), Natitingou (d), Parakou-Airport (e), and Savè (f) stations in the 1970-2015 period

The annual DEF was higher than the SUR in all seasons, which indicated that P is not sufficient to meet the water potential demand (PET) for the system. The annual DEF ranged from 374.7 mm (Cotonou-Airport) to 947.5 mm (Kandi-Airport), with a tendency to increase from the coast (near the Equator) to the north of Benin. The SUR did not show a defined spatial variation pattern, with values between 73.2 mm (Bohicon) and 334.8 mm (Natitingou). Bohicon and Savè (109.1 mm) had similar annual SUR, a similar result occurred in Kandi-Airport (196.9 mm), Cotonou-Airport (228.1 mm), and Parakou-Airport (234.7 mm).

Kandi-Airport, Natitingou, and Parakou-Airport, central and northern Benin, had the longest periods with DEF (eight months, from October to May) and a period of only two (August and September) with SUR or three months (July, August, and September). Regarding the other months, the DEF and SUR were zero. Cotonou-Airport (from November to March and August) and Savè (from November to May) had seven months of DEF and Bohicon six (from November to April). These stations were located in south-central and southern Benin. However, Cotonou-Airport had only two months of SUR (June and July), Savè with three months (August, September, and October), and Bohicon with four (from July to October). The others with null DEF and SUR.

Similar results were observed by several authors who studied changes in Benin's climate (ATIDEGLA *et al.*, 2017; BOKO *et al.*, 2012; DJOHY *et al.*, 2015) and found that Benin had a longer period of water deficit than periods of water surplus in the different seasons.

Climate classification of Benin stations

Based on the data obtained from the climatological water balance (CWB), the climate

classification was carried out following the methodology of Thornthwaite and Mather (1955), which considers in the climate classification the following values of the indexes: water (Ih), aridity (Ia) and humidity (Iu) (Table 6).

It can be seen in Table 6 that the Cotonou-Airport station that the letter C₂ was obtained using the “first key” as a function of Iu, characterizing the Subhumid climate. Through the “second key” and, based on the Ia, the letter w was determined, showing moderate winter deficiency. Using the “third key”, due to the annual PET, the letter A' was observed, indicating Megathermal climate. Finally, with the “fourth key”, as a function of the summer PET ratio (PETs), obtained by the sum of PET from June to August (310.2 mm) and annual PET, the letter a' was determined. Therefore, the climate of this season was C₂wA'a' (Megathermal Subhumid with moderate winter deficiency).

The “first key” for the Bohicon and Savè stations was obtained based on the Iu, for which the typology C₁ was found, therefore indicating Subhumid Dry climate. In the “second key”, based on the Ih, subtype d was determined, which indicated little or no water surplus. As for the “third key”, determined through the annual PET, type A' was determined, which indicated a megathermal climate. Finally, through the “fourth key”, as a function of the relationship between the PETs (305.2 mm – Bohicon and 303.8 mm – Savè) and the annual PET, the a' subtype was determined. Thus, the complete climatic typology of the Bohicon and Savè stations was C₁dA'a', that is, Megathermal Dry Subhumid with little or no water surplus.

The stations of Parakou-Airport and Natitingou showed the same climatic characteristics for the “first key”, obtained based on the Iu, being the typology C₁, which indicated dry Subhumid climate.

Table 6. Climate classification of the stations in Benin through the Thornthwaite and Mather method (1955)

Stations	Ih (%)	Ia (%)		Iu (%)		PET _{Annual}		PET _{summer} /PET _{Annual} (%)	
Bohicon	5.08	28.82	d	-12.21	C ₁	1439.9	A'	21.2	a'
Cotonou-Airport	16.06	26.39	w	0.23	C ₂	1420	A'	21.84	a'
Kandi-Airport	11.23	54.03	s	-21.19	D	1753.5	A'	21.77	a'
Natitingou	22.12	43.89	s ₂	-4.21	C ₁	1513.5	A'	21.15	a'
Parakou-Airport	14.2	45.29	s	-12.97	C ₁	1652.3	A'	20.08	a'
Savè	7.57	33.86	d	-12.75	C ₁	1441.5	A'	21.08	a'

In the “second key”, based on the Ia, the subtypes s_1 (summer moderate surplus) and s_2 (large summer surplus) were determined for Parakou--Airport and Natitingou, respectively. As for the “third key” and “fourth key”, determined employing the annual PET and by the $PETs/PET_{annual}$ ratio, respectively, type A' (Megathermal) and subtype a' were determined for the two seasons. Thus, the complete climatic formula of these stations was Parakou-Airport - $C_1sA'a'$ (Dry Subhumid, Megathermal with moderate summer surplus) and Natitingou - $C_1s_2A'a'$ (Dry Subhumid, Megathermal with large summer surplus). Kandi-Airport, located in the extreme north of the country, on the boundary of the Sahel, presented typology D, in other words, Semi-arid, based on the “first key” of Thornthwaite's classification. The “second key” indicated subtype s_1 (moderate summer surplus). As for the “third key” and “fourth key”, similar to the other stations, type A' (Megathermic) and subtype a' were determined. Thus, the complete climatic classification for this station was $DsA'a'$ (Semi-arid, Megathermal with moderate summer surplus).

These results partially agree with Müller *et al.* (2018), who noted that climate in Benin is of type C (Sub-humid) according to the climate classification of Thornthwaite (1948) and Am-type (predominant class- tropical monsoon climate) according to the climate classification of Köppen, (1900).

CONCLUSIONS

- The rainy (dry) season decreases (increases) from the coast (Cotonou-Airport) to northern Benin (Kandi-Airport) and overlaps with the Boreal summer and part of the autumn (Boreal winter and part of the spring).
- The main weather system responsible for the rainy season is the Intertropical Convergence Zone. However, the orographic effect affects the rainfall of the stations (Natitingou and Parakou-Airport) or a contribution of humidity from the Atlantic Ocean (Cotonou-Airport).
- Based on the climate classification by Thornthwaite and Mather (1955), three main types of climates can be observed (Subhumid, Dry Subhumid, and Semi-arid) in Benin, with variations in water surplus or deficit

and increased aridity from the coast (near the Equator) to the north of Benin:

- Cotonou-Airport characterized by Subhumid Megathermal climate with moderate winter deficit ($C_2wA'a'$);
- Bohicon and Savè with Subhumid Dry Megathermal climate with little or no water surplus ($C_1dA'a'$). Parakou-Airport, with Subhumid Dry Megathermal climate with moderate summer surplus ($C_1sA'a'$) and Natitingou, characterized by Subhumid Dry, Megathermal climate with large summer surplus ($C_1s_2A'a'$);
- Kandi-Airport, Semi-arid, Megathermal climate with moderate summer surplus ($DsA'a'$).
- Due to the decrease in the rainy season and the water surplus from the coast (south) to the north of Benin, the increase in aridity, subsistence, and rainfed agricultural activity presents a greater risk in the north of the country, with a shorter rainy season and surplus and greater aridity.
- The components of the CWB can subsidize the definition of the best planting and harvesting date, the definition of the water demand for the crop and irrigation depth, besides allowing the agricultural zoning planning.

AUTHORSHIP CONTRIBUTION STATEMENT

TODOTE, V.A.L.: Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review & editing; **LYRA, G.B.:** Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing; **ABREU, M.C.:** Methodology, Software, Supervision, Writing – original draft, Writing – review & editing.

DECLARATION OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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REFERENCES

- AHOYO ADJOVI, N. R.; AGBOTON, A. A. G.; QUENUM, F.; MIASSI, Y. E.; DOSSA, F. K.; ADEDEMI, O. Variation climatique et production vivrière au Sud-Bénin : cas de la commune de Bohicon. *Afrique Science*, v. 15(2), p. 32–43, 2018.
- AGBADJAGAN, J. L'Agrométéorologie au Bénin. *Météorologie*, p. 40, 2009.
- AMOUSSOU, E.; TOTIN VODOUNON, S. H.; CLEDJO, F. P.; Y. B. S. ALLAGBE; AKOGNONGBE, J. S. A.; HOUNDENOU, C.; MAHE, G.; CAMBERLIN, P.; BOKO, M.; J PERARD. Evolution climatique du Bénin de 1950 a 2010 et son influence sur les eaux de surface. **XXIXe Colloque de l'Association Internationale de Climatologie, Lausanne - Besançon**, p. 345–350, 2016.
- APARECIDO, L. E. DE O.; ROLIM, G. DE S.; RICHETTI, J.; SOUZA, P. S. DE; JOHANN, J. A. Köppen, Thornthwaite and Camargo climate classifications for climatic zoning in the State of Paraná, Brazil. *Ciencia e Agrotecnologia*, v. 40, n. 4, p. 405–417, 2016.
- ATIDEGLA, S. C.; DÈGLA, H.; SÈNAN, E. Variabilité climatique et production maraîchère dans la plaine inondable d'Ahomey-Gblon au Bénin. *Biological and Chemical Sciences*, v. 11, n. October, p. 2254–2269, 2017.
- BIAOU, A.; DEI, J.-C.; MATHIASSEN, A. Analyse Globale de la Vulnérabilité, de la Sécurité Alimentaire et de la Nutrition (AGVSAN). **Programme Alimentaire Mondial**, p. 146, 2014.
- BOKO, M.; KOSMOWSKI, F.; VISSIN, E. Les Enjeux du Changement Climatique au Bénin. **ResearchGate**, p. 71, 2012.
- CAMARGO, M. N. Delineamento esquemático dos solos do Brasil. *Pesquisa Agropecuária Brasileira*, v. 1, n. 1, p. 47–54, 1966.
- COUTINHO, M. D. L.; COSTA, M. DA S.; SILVA, A. R.; SANTOS, T. S. DOS; GOMES, A. C. DOS S.; MORAIS, M. D. C. DE; SANTOS, P. V. DOS. Balanço hídrico mensal para dois municípios do estado da Paraíba. *Ciência e Natura*, v. 37, n. 3, 2015.
- DJOHY, G.; EDJA, A.; NOUATIN, G. Variation climatique et production vivrière : la culture du maïs dans le système agricole péri-urbain de la commune de Parakou au Nord-Benin. *Afrique Science*, v. 11, n. 6, p. 183–194, 2015.
- ENGELBRECHT, C. J.; ENGELBRECHT, F. A. Shifts in Köppen-Geiger climate zones over southern Africa in relation to key global temperature goals. *Theoretical and Applied Climatology*, v. 123, n. 1–2, p. 247–261, 2016.
- FRERE, M.; POPOV, G. F. agrometeorological crop monitoring and forecasting. **FAO Plant Product Ion And Protection Paper**, v. 17, p. 64, 1979.
- HOLANDA, R. M.; MEDEIROS, R. M. DE. Classificação climática pelo método de Köppen e Thornthwaite em Bom Jesus do Piauí, Brasil. 2018.
- JESUS, J. B. DE. Estimativa do balanço hídrico climatológico e classificação climática pelo método de Thornthwaite e Mather para o município de Aracaju-SE. *Scientia Plena* 2015, v. 11, p. 1–6, 2015.
- JYLHÄ, K.; TUOMENVIRTA, H.; KARHU, J. Observed and projected future shifts of climatic zones in Europe and their use to visualize climate change information. *Weather, Climate, and Society*, v. 2, n. 2, p. 148–167, 2010.
- KÖPPEN, W. Attempting to classify the climates preferably according to their relationship to the plant world. *Geographische Zeitschrift*, v. 6, p. 593–611, 1900.

- MARTINS, F. B.; GONZAGA, G.; SANTOS, D. F. DOS; REBOITA, M. S. Classificação climática de Köppen e de Thornthwaite para Minas Gerais: Cenário atual e projeções futuras. **Revista Brasileira de Climatologia**, v. 22, p. 156, 2018.
- MATOS, F. V. DE; CERQUEIRA, M. B. R.; SILVA, A. W. M.; VELOSO, J. DE C. V.; MORAIS, K. V. A. DE; CALDEIRA, A. P. Egressos da residência de medicina de família e comunidade em Minas Gerais. **Revista Brasileira de Educação Médica**, v. 38, n. 2, p. 198–204, 2014.
- MCSWEENEY, C.; NEW, M.; LIZCANO, G.; LU, X. The UNDP Climate Change Country Profiles. **Bulletin of the American Meteorological Society**, v. 91, n. 2, p. 157–166, 2010.
- MEDEIROS, R. M. DE; AZEVEDO, P. V. DE; SABOYA, L. M. F.; FRANCISCO, P. R. M. Classificação climática e zoneamento agroclimático Para o município de Amarante – PI. **Revista Brasileira de Agricultura Irrigada**, v. 7, n. 2, p. 170–180, 2013.
- MÜLLER, M. DOS S.; DOURADO-NETO, D.; TIMM, L. C.; REICHARDT, K.; SARTORI, F. F.; FELISBERTO, G. Climate analysis for agricultural improvement of the Economic Community of West African States according to Köppen and Thornthwaite. **African Journal of Agricultural Research**, v. 13, n. 23, p. 1198–1212, 2018.
- OBADA, E.; ALAMOU, E. A.; CHABI, A.; ZANDAGBA, J.; AFOUDA, A. Trends and changes in recent and future Penman-Monteith potential evapotranspiration in Benin (West Africa). **Hydrology**, v. 4, n. 3, p. 7–16, 2017.
- OGOUWALE, E. Cadre de Gestion Environnementale et Sociale. Bénin: Editora Météorologie, 2015.
- PASSOS, M. L. V.; ZAMBRZYCKI, G. C.; PEREIRA, R. S. Balanço Hídrico e Classificação Climática para uma determinada região de Chapadinha - Ma. **Revista Brasileira de Agricultura Irrigada**, v. 10, n. 4, p. 758–766, 2016.
- PEREIRA, A. R.; ANGELOCCI, L. R.; SENTELHAS, P. C.; ANTONIO. Fundamentos e Aplicações Práticas. **Agrometeorologia**, p. 478, 2002.
- PRIMO, D. F.; TREVISAN, D. P.; DUARTE, R. T. Análise comparativa de métodos de estimativa de evapotranspiração para fins agrícolas na região de São Carlos – Sp. **Revista brasileira de iniciação científica**, v. 6, n. 1, p. 13–32, 2019.
- ROLIM, G. D. S.; CAMARGO, M. B. P. DE; LANIA, D. G.; MORAES, J. F. L. DE. Climatic classification of köppen and thornthwaite systems and their applicability in the determination of agroclimatic zoning for the state of São Paulo, Brazil. **Bragantia**, v. 66, n. 4, p. 711–720, 2007.
- ROLIM, G.; SENTELHAS, P.; BARBIERE, V. Planilhas no ambiente excel para os cálculos de balanços hídricos: normal, sequencial, de cultura e de produtividade real e potencial. **Revista Brasileira de Agrometeorologia**, v. 6, n. 1, p. 133–137, 1998.
- SILVA, A. O.; MOURA, G. B. A.; KLAR, A. E. Classificação Climática de Thornthwaite e sua aplicabilidade agroclimatológica nos diferentes regimes de precipitação em Pernambuco. **Irriga**, v. 19, n. 1, p. 46, 2014.
- THORNTHWAITE, C. W. An Approach toward a Rational Classification of Climate. **Geographical Review**, v. 38, n. 1, p. 55–94, 1948.
- THORNTHWAITE, C. W.; MATHER, J. R. The water balance. **Publication in Climatology**, v. VIII Num., n. 8, p. 1–104, 1955.
- TONI, H.; DJOSSA, B. A. Economic value of pollination services on crops in Benin, West Africa. **International Journal of Biological and Chemical Sciences**, v. 9, n. 1, p. 225–233, 2015.
- YABI, I.; AFOUDA, F. Extreme rainfall years in Benin (West Africa). **Quaternary International**, v. 262, p. 39–43, 2012.