

Water needs and equivalence relations for different irrigated crops in the São Francisco basin¹

Demanda hídrica e relações de equivalência para diferentes culturas irrigadas na bacia do São Francisco

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ABSTRACT - The present work was performed by applying the principal component analysis, in order to compare the water needs of banana, mango, grape, sugarcane, maize and beans crops in different regions of the São Francisco river basin, aiming to identify the climate elements that most influence the reference evapotranspiration (ET_0) in the locations of Pirapora-MG, Jaíba-MG, Barreiras-BA and Petrolina-PE. In addition, the locations with more similarities, according to the evaluated parameters, were verified by applying cluster analysis, and the equivalence relations between the studied crops were determined by integrating the parameters related to the climatic elements and the characteristics of crops and soils. Based on the principal components analysis, it was observed that the most significant climate elements for ET_0 estimation were different for each place. The model with two components explained 90%, 88%, 95% and 97% of the total variance, respectively for the locations of Pirapora, Jaíba, Barreiras and Petrolina. Because it is in a semi-arid climate region, Petrolina showed high crop water needs, a behavior proven with the cluster analysis. The equivalence relations allowed comparing the water needs for the studied crops, providing, in general terms, a parameter comparison between the crops, and specifying which one will be more adequate depending on the water availability in the São Francisco basin.

Key words: Irrigated agriculture. Crop water balance. Climatic parameters. Evapotranspiration.

RESUMO - O presente trabalho foi conduzido aplicando a estatística multivariada de componentes principais para comparar as demandas hídricas das culturas da banana, manga, uva, cana de açúcar, milho e feijão em diferentes regiões da bacia do rio São Francisco, visando identificar os elementos climáticos que mais influenciam a evapotranspiração de referência (ET_0) nas localidades de Pirapora-MG, Jaíba-MG, Barreiras-BA e Petrolina-PE. Adicionalmente, procurou-se identificar as localidades que apresentam maior semelhança em relação aos parâmetros avaliados, por meio da aplicação da análise de cluster, e determinar as relações de equivalência entre as culturas estudadas, integrando os parâmetros relativos aos elementos climáticos e às características das culturas e do solo. Com base na estatística multivariada de componentes principais, identificou-se que os elementos climáticos que possuem maior significância na estimativa da ET_0 foram distintos para cada local. O modelo com duas componentes explicou 90%, 88%, 95% e 97% da variância total para as localidades de Pirapora, Jaíba, Barreiras e Petrolina, respectivamente. Por estar situada em uma região de clima semiárido, Petrolina apresentou elevada demanda hídrica pelas culturas, sendo comprovado este comportamento com a análise de cluster. As relações de equivalência permitiram comparar as demandas hídricas das diferentes culturas, fornecendo, em termos gerais, um parâmetro comparativo entre as culturas, e discriminando qual cultura será mais adequada em função da disponibilidade hídrica na bacia do rio São Francisco.

Palavras-chave: Agricultura irrigada. Balanço hídrico. Parâmetros climáticos. Evapotranspiração.

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INTRODUCTION

The São Francisco River basin covers an area of 638,466 km², representing 7.5% of the national territory. Most of the basin (58%) is in a semi-arid region, which explains the low average annual precipitation (1,033 mm) when compared to the national average (1,761 mm), and extended periods of drought and high evapotranspiration are frequent (AGÊNCIA NACIONAL DE ÁGUAS, 2013).

Evapotranspiration is the most representative parameter to set crop water needs, and it is based on the combination of climatic elements such as maximum and minimum temperature, sunshine hours or solar radiation, wind speed and relative humidity (ALENCAR; SEDIYAMA; MANTOVANI, 2015; WIDMOSER, 2009). Crop evapotranspiration represents the main process of groundwater loss, directly affecting the availability and sustainability of water resources, and, consequently, the growth of plants (LANGENSIEPEN *et al.*, 2009). Knowing it is essential in applications related to the areas of hydrology, climate change impacts and droughts (SENATORE *et al.*, 2015).

Determination of the relative effects of the elements which influence the process of evapotranspiration is of significant importance within the context of irrigated agriculture, especially in semi-arid climate areas. By means of these considerations, it is possible to define the best strategy for the rational use of water (ANDRADE; SILVEIRA; AZEVEDO, 2003).

Therefore, multivariate statistics applied to principal components analysis may be used to define a set of variables that explain the maximum of the variance function. For this purpose, a linear combination of data is used to determine the variables which most influence the evapotranspiration process in each location (ARRUDA *et al.*, 2012; ISLABÃO *et al.*, 2013; MANDAL *et al.*, 2008; REID; SPENCER, 2009).

Multivariate statistics may also be employed for the grouping between individuals based on their characteristics. The criterion for the formation of groups is the homogeneity within the group and the differences between them (HATVANI *et al.*, 2011; RUHOFF; SALDANHA; COLLISCHONN, 2009).

Knowledge of the water need of different crops in places at which there is the possibility of conflict due to the use of water is of great value, once this allows for the development of equivalence relations among crops and provides guidance for the zoning or allocation of crops in a given region, in a water crisis scenario.

In this context, the objectives of this study were: (1) to identify the climatic elements that most influence

the reference evapotranspiration (ET_0) at four locations in the São Francisco river basin using multivariate statistics with principal component analysis; (2) to estimate the average ET_0 for a period of 10 years with the purpose of assessing the similarity among locations regarding this parameter using cluster analysis; (3) to determine the water need of crops to be supplied via irrigation, and the equivalence relations for banana, mango, grape, sugarcane, maize and beans crops, integrating the parameters related to climatic elements and to the characteristics of the crops and soil.

MATERIAL AND METHODS

The locations used in this study were Pirapora-MG, Jaíba-MG, Barreiras-BA and Petrolina-PE. They were chosen because they are in regions with a significant area of irrigated agriculture, for presenting distinct climatic characteristics and availability of historical series of climate data. The Pirapora region lies in the region of the upper São Francisco, being characterized by the Aw climate, according to the Köppen climate classification, which is described as being a Tropical climate with the occurrence of rain in the summer and having a dry winter, as shown in Figure 1a. Jaíba and Barreiras are located in the region of the Medium São Francisco; however, Barreiras also presents the Aw-type climate, while Jaíba has the As-type climate characterized as a Tropical climate with a dry summer. According to Alvares *et al.* (2013), Petrolina is in the sub-medium region of the São Francisco River and has the BSh-type climate, that is, a dry, semi-arid climate, whose occurrence is common in regions of low latitudes and altitudes. As shown in table 1, the altitude of the weather stations varies from 370 m to 505 m, in Petrolina and Pirapora, respectively. Figure 1b shows the digital model of the elevation of the São Francisco river basin, in which it is possible to see the spatialization of the altimetry of the basin.

Table 1 shows the information of the weather stations used in the study and Table 2 shows the years with availability of data for the locations studied.

Maximum temperature (T_{max}) and minimum temperature (T_{min}) data were obtained in Celsius degrees (°C); number of sunshine hours (S) in hours; average relative humidity (RH) in percentage; average wind speed (W) in m s⁻¹; and precipitation (P) in mm. All parameters were obtained daily from the National Institute of Meteorology (INMET).

The use of a period of 10 years of data was established due to the availability of data at the weather stations used in the study. The crop water need was estimated based on the simulation of the crop water balance on a daily

scale, according to the methodology described in FAO 56 (ALLEN *et al.*, 1998). For this purpose, it was necessary to estimate the average reference evapotranspiration for

each day of the year, for each of the 10 years of data, in order to obtain a year of daily average data of reference evapotranspiration.

Figure 1 - Climate types (a) and digital elevation model (b) of the São Francisco basin

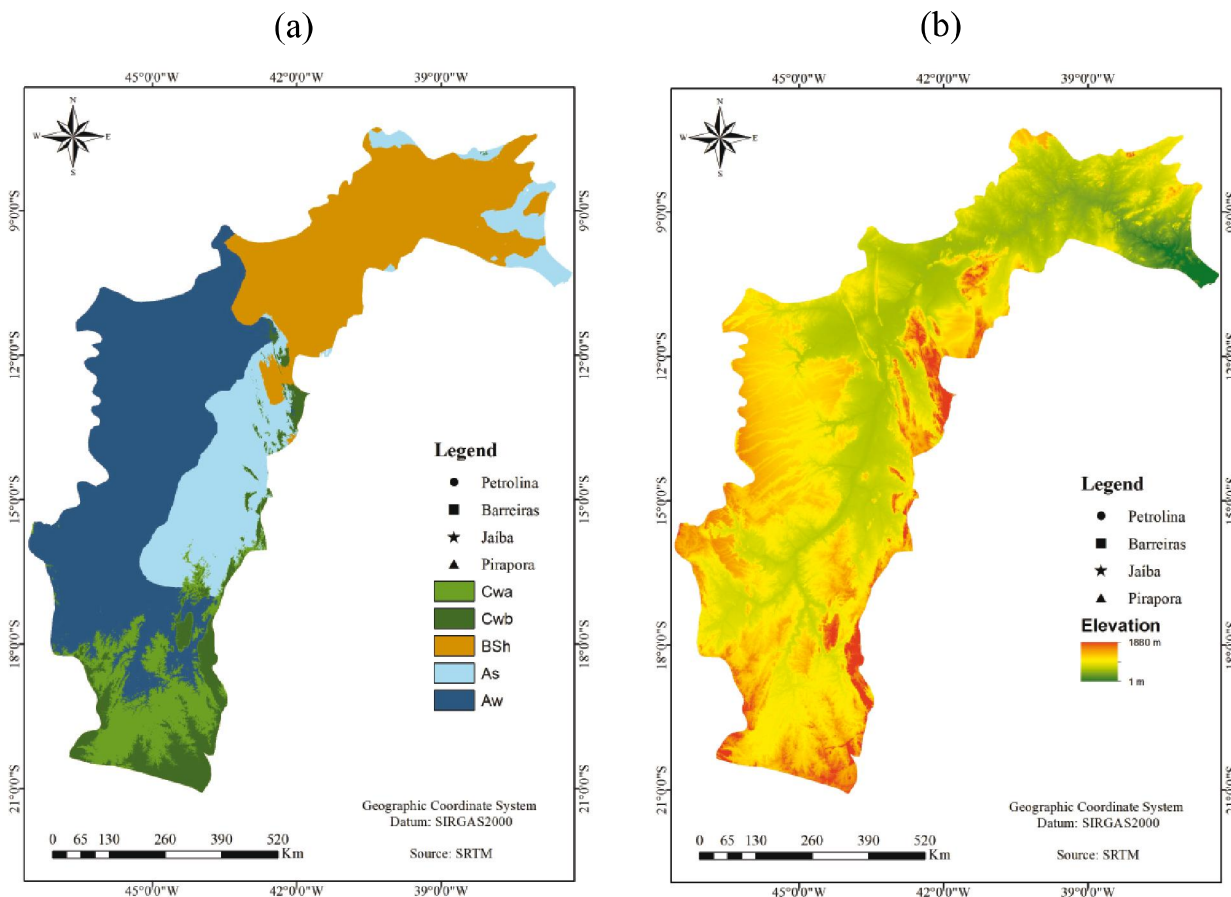


Table 1 - Geographic coordinates of the weather stations where data were collected

Weather station	Code	Latitude (°)	Longitude (°)	Elevation (m)
Pirapora-MG	83483	-17.35	-44.91	505.24
Mocaminho/Jaíba-MG	83389	-15.08	-44.01	452.00
Barreiras-BA	83236	-12.15	-45.00	439.29
Petrolina-PE	82983	-9.38	-40.48	370.46

Table 2 - Years of data selected in each weather station to estimate ET_0

Weather station	Selected Years
Pirapora-MG	1970, 1976, 1990, 1991, 1999, 2000, 2003, 2006, 2011, 2012
Mocaminho/Jaíba-MG	1986, 1987, 1988, 1991, 1996, 1997, 2000, 2001, 2002, 2009
Barreiras-BA	1967, 1969, 1970, 1978, 1979, 2001, 2002, 2003, 2006, 2007
Petrolina-PE	1973, 1975, 2003, 2006, 2007, 2009, 2010, 2011, 2012, 2013

The evapotranspiration of banana, mango, grape, maize, beans and sugarcane crops was estimated daily, taking into consideration the reference evapotranspiration (ET_0), daily average of 10 years, the crop coefficient K_c (initial, middle and final), and the soil water stress coefficient K_s , according to Equation 1.

$$ET_c = ET_0 \cdot K_c \cdot K_s \tag{1}$$

where: ET_c = crop evapotranspiration (mm d^{-1}); ET_0 = reference evapotranspiration (mm d^{-1}); K_c = crop coefficient, dimensionless; K_s = soil water stress coefficient, dimensionless. The values of K_s were simulated daily considering the humidity of the soil on that day, according to the methodology described in FAO 56 (ALLEN *et al.*, 1998).

The estimates of ET_0 for the weather stations of the studied places were performed with the Penman-Monteith method, according to the model published in FAO 56 (ALLEN *et al.*, 1998), since this is considered the most accurate compared to the other existing indirect methods (CAI *et al.*, 2007; GAVILAN; BERENGENA; ALLEN, 2007; SENTELHAS; GILLESPIE; SANTOS, 2010; XING *et al.*, 2008).

The research was performed considering the simulation within the period of one year. Therefore, the growing of one cycle of bananas, one cycle of mangoes, two cycles of grapes and one crop of sugarcane was standardized according to the common agricultural crop calendar in these regions. Besides the aforementioned crops, for each place, two maize crops were planted in a row in rotation with one cycle of beans.

In this case, the first sowing of maize happened in October and the harvest was in January of the following year, the sowing of the subsequent maize crop occurred in February and the harvest in May, and the sowing of beans took place in mid-June and the harvest in September. The crop calendar used in this study is shown in Table 3, in which it is possible to observe the beginning of each cycle of the perennial crops and the implementation of annual crops.

For simulation purposes, the table of Appendix 8 of the FAO Bulletin 56 was adopted; however, using the crop coefficient (K_c), which encompasses the average effects of evaporation on soil and plant transpiration into one single coefficient for each phenological phase of the crop (ALLEN *et al.*, 1998). The input parameters in the model from Appendix 8 of FAO 56 are the values of K_c of each phenological phase (Table 4) and the lengths of the respective development stages (Table 5). The table estimates, for each day of simulation, one value of $K_c \cdot K_s$. For this purpose, it considers crop development, considering inherent characteristics of each crop (depth of the roots system, maximum plant height), as well as soil and climatic elements (wind speed and relative humidity).

Whenever possible, parameters obtained in the experiments performed in the studied places were adopted, both for the values of K_c and for the length of the development phases, as can be observed in the references used in Tables 4 and 5. In the absence of these, tabulated values from publication 56 of FAO were used (ALLEN *et al.*, 1998). In order to make the simulations closer to local conditions, the physical attributes of the soils of the region were used and they are shown in Table 6.

To obtain the equivalence relations among crops, initially, the water requirements of each crop and at each irrigated perimeter were grouped annually with the intention of obtaining the average annual water need to be supplied via irrigation, that is, considering the average local rainfall regime.

Equivalence relations ultimately aim to compare the water needs of the crops of the distinct regions to be supplied via irrigation. For this purpose, the calculation was performed by comparing the water needs of a crop at various places, or by comparing the water needs of several crops at the same place.

The model of multivariate statistics of principal components was used to identify the climatic parameters that have greater importance to the estimation of ET_0 .

Table 3 - Crop calendar standardized for banana, mango, grape, sugarcane, maize and beans crops

Crops	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Banana	Planting	----->										Harvest	
Mango	----->										Harvest	Planting	----->
Grape	----->					Harvest	Planting	----->					
Sugarcane	----->										Harvest	Planting	----->
Maize/Beans	Harvest	Planting	----->			Harvest	Planting	----->		Harvest	Planting	----->	

Table 4 - Values adopted for Kc_{ini} , Kc_{mid} and Kc_{end} for banana, mango, grape, sugarcane, maize and beans crops

Crops	Kcini	Kcmid	Kcend	Source
Banana	1.00	1.20	1.10	Allen <i>et al.</i> (1998)
Mango	0.70	1.00	0.60	Teixeira <i>et al.</i> (2008)
Grape	0.30	0.85	0.45	Allen <i>et al.</i> (1998)
Sugarcane	0.75	0.87	0.52	Carmo (2013)
Maize	0.50	1.20	0.60	Doorenbos and Kassan (1979)
Beans	0.40	1.15	0.35	Allen <i>et al.</i> (1998)

Table 5 - Values adopted for the length of each phase of the cycle, in days, for banana, mango, grape, maize and beans crops

Crops	Lini	Ldev	Lmid	Lend	Source
Banana	120	60	180	5	Allen <i>et al.</i> (1998)
Mango	30	100	95	70	Embrapa (2005)
Grape	30	40	75	15	Freitas, Ramos and Costa (2006)
Sugarcane	22	90	195	41	Carmo (2013)
Maize	20	35	40	25	Allen <i>et al.</i> (1998)
Beans	15	25	30	20	Allen <i>et al.</i> (1998)

L_{ini} , L_{dev} , L_{mid} , L_{end} - length of the initial, development, middle and final phases of the phenological cycle

Table 6 - Physical attributes of the soil adopted for Pirapora, Jaíba, Barreiras and Petrolina

Attributes	Pirapora	Jaíba	Barreiras	Petrolina
	Predominant soil types			
	Entisol ¹	Entisol (Quartzipsamments) ²	Red-Yellow Ultisol ³	Entisol (Quartzipsamments) ⁴
Sand (%)	57.00	85.00	52.00	93.81
Silt (%)	26.00	7.00	23.00	0.63
Clay (%)	17.00	8.00	25.00	5.56
θ_{cc} (% volume)	17.88	13.96	27.80	11.90
θ_{pmp} (% volume)	10.43	6.02	15.10	2.90
Total available water (mm m ⁻¹)	74.50	79.40	127.44	90.00

Source: 1 - Medeiros (2002); 2 - Moura (2007); 3 - Oliveira, Silva and Campos. (1979); 4 - Nascimento (2009)

Thus, standardization of data was necessary in order to match their units and scales. The average of 10 years for each climatic element at each location, and monthly, was used as follows:

$$Y_{ij} = \frac{X_{ij} - \bar{X}_i}{S_i} \quad (2)$$

where, X_{ij} = value observed for the j_{th} repetition of the i_{th} climatic factor; \bar{X}_i = average of the climatic factor i ; S_i = standard deviation of the climatic factor i ; Y_{ij} = standardized value.

For the principal component analysis, climatic elements were used monthly, unlike the water balance,

which was performed on a daily basis. After extraction, the components presented difficult interpretation and, because of that, the Varimax algorithm was used as a matrix orthogonal rotation procedure (ANDRADE *et al.*, 2007).

Cluster analysis was applied to group the locations that showed similarity regarding the climatic elements; considering maximum temperature (Tmax), minimum temperature (Tmin), sunshine hours (S), average relative humidity (RH) and average wind speed (WS), all monthly. In this study, the Euclidean distance between two vectors, and complete linkage as the agglomerative method were used (RUHOFF; SALDANHA; COLLISCHONN, 2009).

RESULTS AND DISCUSSION

Table 7 shows the results for the principal component analysis. It is possible to observe that the model with two components explained 90%, 88%, 95% and 97% of the total variance for the locations of Pirapora, Jaíba, Barreiras and Petrolina, respectively. It can be stated, such as Andrade, Silveira and Azevedo (2003) did, that the model is capable of combining the information previously distributed in six variables into only two components.

The proposal of Norusis (1990), which states that a component can be used if it presents an eigenvalue above 1, was used as theoretical basis in order to define the model with two variables. It is also important to observe that the first component was responsible for explaining more than 53% of the total variance at all studied locations. Guedes *et al.* (2012) emphasize that one of the main characteristics of the components is related to how they are obtained, being presented in descending order; the first component explains most part of the total variance of data and the second one explains the maximum of variance of the rest of the data, and it is not correlated with the first one.

By analyzing Table 8 for the region of Pirapora, the climatic elements that were more important for

the first component were minimum and maximum temperature and sunshine hours. Based on this finding, it can be observed that this component is correlated with the heating of the atmosphere close to the surface.

Regarding Jaíba, the climatic factor that was more significant was relative humidity, followed by wind speed, minimum temperature and sunshine hours. In this case, it can be said that the climatic elements with significant importance to this element (RH, I) are correlated with vapor pressure deficit, that is, by the gradient which promotes the ET_0 process.

Nevertheless, when it comes to Barreiras, located in the same region as Jaíba (region of the Medium São Francisco), the most significant parameters were maximum temperature, relative humidity and wind speed. For Petrolina, minimum temperature, wind speed and maximum temperature were the most significant parameters.

The observed differences regarding the crop water needs are mostly explained by the climatic elements that determine the evapotranspiration process. The region of Pirapora presents a milder climate compared to the other locations (Figures 2a and 2b).

Table 7 - Results of eigenvalues, variances and cumulative variances for Pirapora, Jaíba, Barreiras and Petrolina

Locations	Components	Eigenvalue	Variance (%)	Cumulative Variance
Pirapora	1	2.693978	53.87956	53.8796
	2	1.823638	36.47276	90.3523
	3	0.418466	8.36932	98.7216
	4	0.062455	1.24910	99.9707
	5	0.001463	0.02926	100.0000
Jaíba	1	3.000693	60.01387	60.0139
	2	1.412291	28.24583	88.2597
	3	0.562614	11.25227	99.5120
	4	0.022831	0.45662	99.9686
	5	0.001570	0.03141	100.0000
Barreiras	1	3.505653	70.11307	70.1131
	2	1.288722	25.77443	95.8875
	3	0.174703	3.49405	99.3815
	4	0.027290	0.54580	99.9273
	5	0.003633	0.07265	100.0000
Petrolina	1	2.906988	58.13976	58.1398
	2	1.979998	39.59996	97.7397
	3	0.082304	1.64607	99.3858
	4	0.027471	0.54942	99.9352
	5	0.003240	0.06479	100.0000

Table 8 - Results of the factors after rotation of the component for Pirapora, Jaíba, Barreiras and Petrolina

Locations	Climatic elements	Factor 1	Factor 2
Pirapora	Tmax	0.844745	-0.383295
	Tmin	0.983809	0.132279
	S	-0.829353	-0.335932
	RH	0.417383	0.896081
	WS	0.168449	-0.930327
Jaíba	Tmax	-0.107762	-0.962825
	Tmin	0.776107	-0.623021
	S	-0.720485	0.330337
	RH	0.983542	0.131487
	WS	-0.913809	-0.189561
Barreiras	Tmax	-0.977087	-0.058379
	Tmin	0.085386	-0.993535
	S	-0.311470	0.928423
	RH	0.858213	-0.500395
	WS	-0.848723	0.419079
Petrolina	Tmax	0.777043	0.624881
	Tmin	0.988448	0.099598
	S	-0.023232	0.977431
	RH	-0.056229	-0.985266
	WS	-0.973809	0.166250

Due to the low rainfall characteristic of semi-arid regions (Figure 2c), Petrolina presents little variation in average monthly sunshine hours throughout the year (Figure 2d), as well as high occurrence of wind (Figure 2e) and low relative humidity (Figure 2f). For this location, maximum temperature values ranging from 29.1 to 35.4 °C were registered throughout the year, and Teixeira (2010) obtained values between 29.6 and 34.0 °C for Petrolina between 1965 and 2009.

The average annual precipitation of 10 years obtained for Petrolina is approximately 425 mm while for Pirapora, Jaíba and Barreiras it is around 1,015 mm, 835 mm and 1,060 mm, respectively. According to the Brazilian Climatological Normals of 1961-1990, the accumulated precipitations for the cities of Pirapora, Jaíba, Barreiras and Petrolina are, respectively, 1,057 mm; 805.2 mm (excluding the month of March for lack of data); 1,140 mm and 577.4 mm.

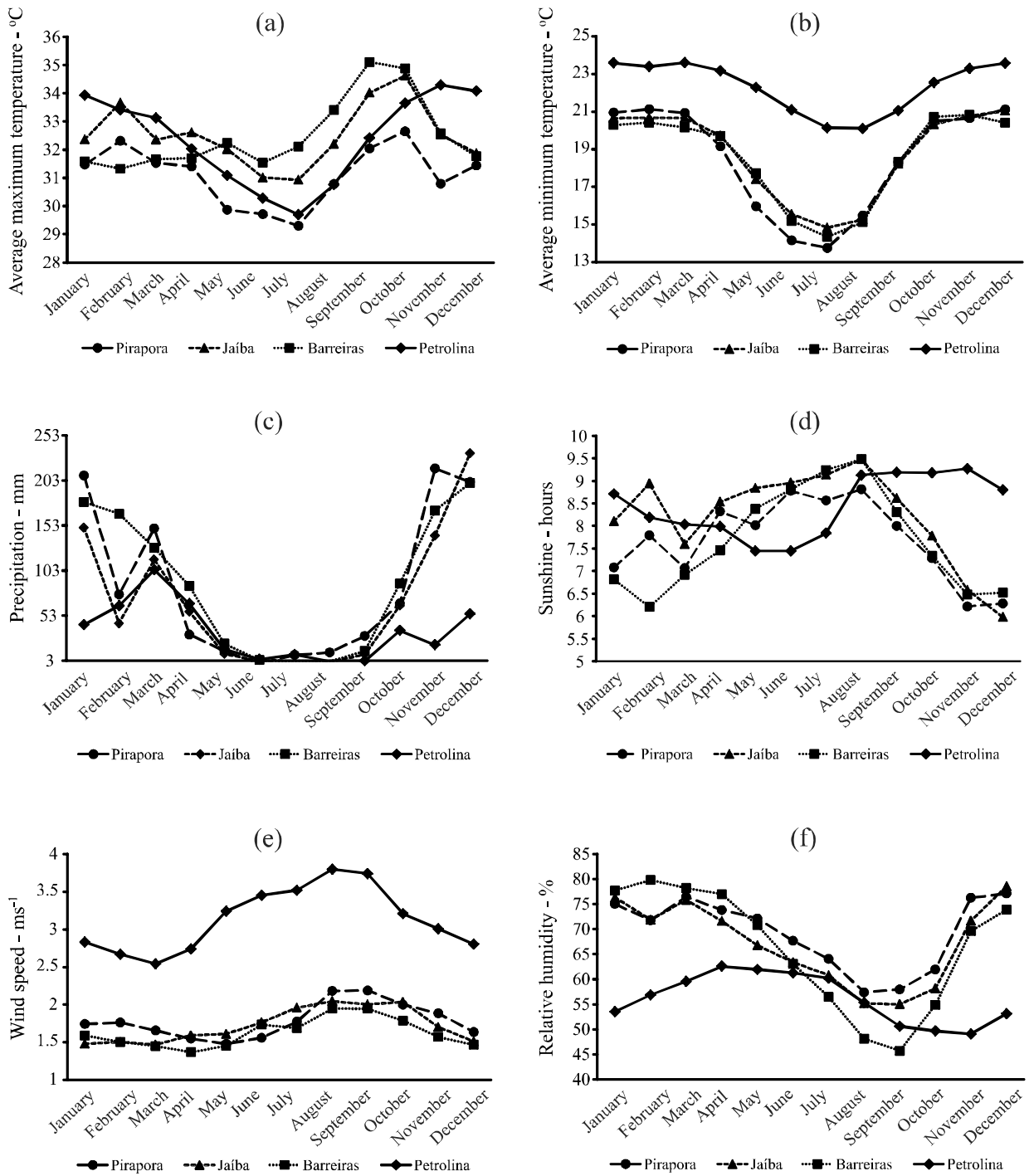
Since the climate of where Petrolina is located is semi-arid, the greater the water need of crops in the region, once, according to Allen *et al.* (1998), moist fields in arid (hot and dry) regions lose large quantities of water that are transferred to the atmosphere due to the process

of evapotranspiration because of the large quantity of energy available combined with the high moisture holding capacity of air (Figure 3a).

In Figure 3b, the distinction of locations can be observed due to the existing differences among them, considering the reference evapotranspiration, maximum temperature, minimum temperature, sunshine hours, relative humidity, wind speed and precipitation, using Cluster analysis as grouping technique. Barreiras and Pirapora were put in the same group, because they are located in regions of Aw climate, according to the Köppen classification, which is characterized as Tropical with occurrence of rain in the summer and dry winter (Figure 1a), thus, having similar climatic characteristics.

Jaíba is situated in a region of transition from the semi-humid tropical climate to the semi-arid tropical climate, unlike Barreiras and Pirapora, having an intermediate position regarding the semi-humid and semi-arid tropical climates. The location of Petrolina is of semi-arid tropical climate and was classified as distinct from the other regions, which is explained by the fact that the climatic parameters of this region are considerably different from the other regions, as previously mentioned.

Figure 2 - Monthly average behavior of the maximum temperature (a), minimum temperature (b), precipitation (c), sunshine hours (d), wind speed (e) and relative humidity (f)



Integration of the parameters relating to climate, and to the physiological characteristics of crops and soil can be evidenced in the equivalence relations between the crops of banana, mango, grape, sugarcane, maize and

beans, in the locations studied (Figure 4). The equivalence relations were obtained by the ratio between the average annual water need of the crop (columns) and the average annual water need of the crop (lines).

Figure 3 - Monthly behavior of evapotranspiration for the studied places (a) and application of cluster analysis to the evapotranspiration data for the studied places (b)

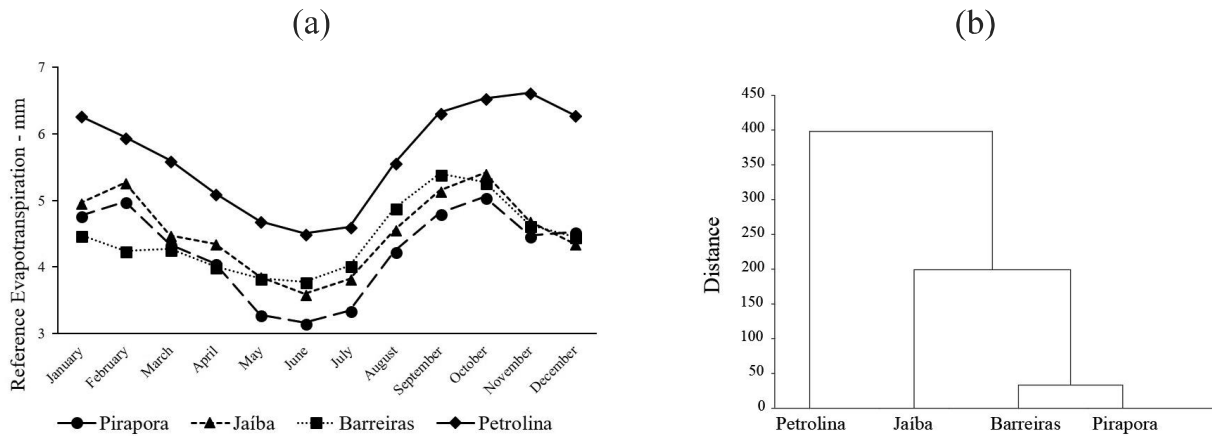


Figure 4 - Equivalence relations among the water needs for irrigation of banana, mango, grape, sugarcane, maize and beans crops for the studied places

	Pirapora MG					Jaíba/MG					Barreiras/BA					Petrolina/PE					
	Banana	Mango	Grape	Sugarcane	M/B	Banana	Mango	Grape	Sugarcane	M/B	Banana	Mango	Grape	Sugarcane	M/B	Banana	Mango	Grape	Sugarcane	M/B	
Pirapora/MG	1.00																				
Banana	0.46	1.00																			
Mango	0.51	1.12	1.00																		
Grape	0.60	1.31	1.17	1.00																	
Sugarcane	0.55	1.18	1.08	1.09	1.00																
M/B						1.00															
Jaíba/MG						1.25	2.73	2.44	2.08	2.26	1.00										
Banana	0.62	1.35	1.21	1.03	1.12	0.49	1.00														
Mango	0.64	1.39	1.25	1.06	1.15	0.51	1.03	1.00													
Grape	0.77	1.68	1.50	1.28	1.39	0.62	1.25	1.21	1.00												
Sugarcane	0.73	1.60	1.43	1.22	1.32	0.59	1.18	1.15	0.95	1.00											
M/B											1.00										
Barreiras/BA											1.05	2.30	2.06	1.75	1.91	0.84	1.71	1.65	1.37	1.44	1.00
Banana	0.38	0.84	0.60	0.64	0.70	0.31	0.62	0.60	0.50	0.53	0.37	1.00									
Mango	0.54	1.18	1.05	0.90	0.98	0.43	0.87	0.85	0.70	0.74	0.51	1.40	1.00								
Grape	0.63	1.38	1.24	1.05	1.15	0.51	1.02	0.99	0.82	0.86	0.60	1.64	1.17	1.00							
Sugarcane	0.52	1.14	1.02	0.87	0.94	0.42	0.84	0.82	0.68	0.71	0.49	1.36	0.97	0.82	1.00						
M/B																1.00					
Petrolina/PE																2.06	4.51	4.03	3.43	3.73	2.26
Banana	1.14	2.49	2.22	1.89	2.06	0.91	1.84	1.78	1.48	1.55	1.08	2.96	2.11	1.80	2.18	0.55	1.00				
Mango	1.40	2.03	1.81	1.54	1.68	0.74	1.50	1.45	1.20	1.27	0.88	2.41	1.72	1.47	1.78	0.45	0.81	1.00			
Grape	1.40	3.06	2.73	2.33	2.53	1.12	2.26	2.20	1.82	1.91	1.33	3.64	2.59	2.21	2.68	0.68	1.23	1.51	1.00		
Sugarcane	1.34	2.93	2.61	2.23	2.42	1.07	2.17	2.10	1.74	1.83	1.27	3.48	2.48	2.12	2.57	0.65	1.18	1.44	0.96	1.00	
M/B																					

M/B = Maize and beans rotation

The values shown by the same shades of gray in Figure 4 refer to the equivalence relations among crops in the same place, corresponding to Pirapora, Jaíba, Barreiras and Petrolina, in this order. The values in white refer to the equivalence relations among crops which are in different places.

Among the several relationships between crops at the different locations, some stand out due to the high discrepancy in water layers. For example, the banana crop grown in Petrolina requires an irrigation plate 4.5 times larger than that of the grape crop grown in Pirapora, which can be explained by the climatic difference between

these two places, by the soil type and physiological characteristics of the crops. Thus, irrigation of large areas of banana crops, which have a high water need, promotes great impact on water resources in the region, mainly in areas where rainfall is insufficient to meet the water need of crops.

Equivalence relations are nothing but an index which compares the water need of a crop in relation to another, both for distinct locations and for the same location, and it can be used to evaluate the crop water need via irrigation to identify which crop will be, in general, better used in function of the water availability of the region, provided that the conditions, the methodology and the parameters used in this studied are applied.

Therefore, the application the equivalence relations can be used by decision makers for a better planning and management of water resources, aiming for a rational use of water by means of policies that encourage the growing of certain crops in places where there is water surplus for irrigation, while they may also be a restrictive parameter for the growing of crops in regions where there is shortage of water for irrigation.

CONCLUSIONS

1. The model with two components explained 90%, 88%, 95% and 97% of the total variance for the locations of Pirapora, Jaíba, Barreiras and Petrolina. The climatic elements that most influenced the reference evapotranspiration were: in Pirapora, the minimum temperature; in Jaíba, relative humidity; in Barreiras, the maximum temperature; and in Petrolina, the minimum temperature;
2. According to cluster analysis, Barreiras and Pirapora are regions with similar climatic conditions. Jaíba is in an intermediate position and Petrolina differs from the other locations.
3. In general, the equivalence relations can predict which crop is more indicated regarding the water need to be supplied by irrigation, according to the water availability of each place of study.

REFERENCES

AGÊNCIA NACIONAL DE ÁGUAS (BRASIL). **Conjuntura dos recursos hídricos no Brasil**. Brasília, 2013. 432 p.

ALENCAR, L. P. de; SEDIYAMA, G. C.; MANTOVANI, E. C. Estimativa da evapotranspiração de referência (ET_o Padrão FAO), para Minas Gerais, na ausência de alguns dados climáticos. **Revista Engenharia Agrícola**, v. 35, n. 1, p. 39-50, 2015.

ALLEN, R. G. *et al.* **Crop evapotranspiration**: guidelines for computing crop water requirements. Rome: FAO, 1998. 300 p. (FAO. Irrigation and Drainage Paper, 56).

ALVARES, C. A. *et al.* Koppen's climate classification map for Brazil. **Meteorologische Zeitschrift**, v. 22, n. 6, p. 711-728, 2013.

ANDRADE, E. M. de; SILVEIRA, S. S.; AZEVEDO, B. M. de. Investigação da estrutura multivariada da evapotranspiração na Região Centro Sul do Ceará pela análise de componentes principais. **Revista Brasileira de Recursos Hídricos**, v. 8, n. 1, p. 39-44, 2003.

ANDRADE, E. M. de *et al.* Seleção dos indicadores da qualidade das águas superficiais pelo emprego da análise multivariada. **Revista Engenharia Agrícola**, v. 27, p. 683-690, 2007.

ARRUDA, N. P. *et al.* Correlação entre precursores e voláteis em café arábica brasileiro processado pelas vias seca, semiúmida e úmida e discriminação através da análise por componentes principais. **Química Nova**, v. 35, n. 10, p. 2044-2051, 2012.

CAI, J. *et al.* Estimating reference evapotranspiration with the FAO Penman-Monteith equation using daily weather forecast messages. **Agricultural and Forest Meteorology**, v. 145, p. 22-35, 2007.

CARMO, J. F. A. do. **Evapotranspiração da cana de açúcar irrigada por gotejamento subsuperficial no Submédio do Vale do São Francisco**. 2013. 86 f. Dissertação (Mestrado em Engenharia Agrícola) - Universidade Federal do Vale do São Francisco, Juazeiro, BA, 2013.

DOORENBOS, J.; KASSAM, A. H. **Yield response to water**. Rome: FAO, 1979. 193 p. (FAO. Irrigation and Drainage Paper, 33).

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA. SIMPÓSIO DE MANGA DO VALE DO SÃO FRANCISCO, 1., 2005, Juazeiro. **Palestras...** Petrolina: Embrapa Semi-Árido, 2005. 295 p.

FREITAS, W. S.; RAMOS, M. M.; COSTA, S. L. Demanda de irrigação da cultura da uva na bacia do rio São Francisco. **Revista Engenharia Agrícola**, v. 10, n. 3, p. 563-569, 2006.

GAVILAN, P.; BERENGENA, J.; ALLEN, R. G. Measuring versus estimating net radiation and soil heat flux: impact on Penman-Monteith reference ET estimates in semiarid regions. **Agricultural Water Management**, v. 89 n. 3, p. 275-286, 2007.

GUEDES, H. A. S. *et al.* Aplicação da análise estatística multivariada no estudo da qualidade da água do Rio Pomba, MG. **Revista Engenharia Agrícola**, v. 16, n. 5, p. 558-563, 2012.

HATVANI, G. I. *et al.* Analysis of long-term water quality changes in the Kis-Balaton Water Protection System with time series, cluster analysis and Wilk's lambda distribution. **Ecological Engineering**, v. 37, p. 629-635, 2011.

ISLABÃO, G. O. *et al.* Characterization of soil chemical properties of strawberry fields using principal component

- analysis. **Revista Brasileira de Ciência do Solo**, v. 37, n. 1, p. 168-176, 2013.
- LANGENSIEPEN, M. *et al.* Quantifying the uncertainties of transpiration calculations with the Penman–Monteith equation under different climate and optimum water supply conditions. **Agricultural and Forest Meteorology**, v. 149, n. 6/7, p. 1063-1072, 2009.
- MANDAL, U. K. *et al.* Evaluating impact of irrigation water quality on a calcareous clay soil using principal component analysis. **Geoderma**, v. 144, n. 1/2, p. 189-197, 2008.
- MEDEIROS, S. de S. **Indicadores para gerenciamento do uso da água no perímetro irrigado de Pirapora - MG**. 2002. 125 f. Dissertação (Mestrado Engenharia Agrícola) - Universidade Federal de Viçosa, Viçosa, MG, 2002.
- MOURA, B. R. de. **Avaliação do uso da água em fruteiras irrigadas no projeto Jaíba**. 2007. 115 f. Dissertação (Mestrado Meteorologia Agrícola) - Universidade Federal de Viçosa, Viçosa, MG, 2007.
- NASCIMENTO, P. dos S. **Análise do uso da curva de retenção de água no solo determinada por diferentes métodos e planilha para manejo da irrigação**. 2009. 93 f. Dissertação (Mestrado em Ciências Agrárias) - Universidade Federal do Recôncavo da Bahia, Cruz das Almas, 2009.
- NORUSIS, M. J. **SPSS Base System User's Guide**. Chicago, 1990. 520 p.
- OLIVEIRA, F. A.; SILVA, J. I. S.; CAMPOS, T. G. Evapotranspiração e desenvolvimento radicular do milho irrigado. **Pesquisa Agropecuária Brasileira**, v. 28, p. 1407-1415, 1979.
- REID, M. K.; SPENCER, K. L. Use of principal components analysis (PCA) on estuarine sediment datasets: the effect of data pre-treatment. **Environmental Pollution**, v. 157, p. 2275-2281, 2009.
- RUHOFF, A. L., SALDANHA, C. B., COLLISCHONN, W. Análise multivariada do processo de evapotranspiração em áreas de cerrado e cana-de-açúcar. **Revista Brasileira de Recursos Hídricos**, v. 14, n. 4, p. 137-146, 2009.
- SENATORE, A. *et al.* Regional scale modeling of reference evapotranspiration: intercomparison of two simplified temperature and radiation-based approaches. **Journal of Irrigation Drainage Engineering**, v. 141, n. 12, 2015.
- SENTELHAS, P. C., GILLESPIE, T. J., SANTOS, E. A. Evaluation of FAO Penman–Monteith and alternative methods for estimating reference evapotranspiration with missing data in Southern Ontario, Canadá. **Agricultural Water Management**, v. 97, n. 5, p. 635-644, 2010.
- TEIXEIRA, A. H. de C. *et al.* Energy and water balance measurements for water productivity analysis in irrigated mango trees, Northeast Brazil. **Agricultural and Forest Meteorology**, v. 148, p. 1524-1537, 2008.
- TEIXEIRA, A. H. de C. **Informações agrometeorológicas do Polo Petrolina, PE/ Juazeiro, Ba - 1963 a 2009**. Petrolina: Embrapa Semiárido, 2010. 23 p.
- WIDMOSER, P. A discussion on and alternative to the Penman-Monteith equation. **Agricultural and Forest Meteorology**, v. 96, n. 4, p. 711-721, 2009.
- XING, Z. *et al.* Validating evapotranspiration equations using Bowen Ratio in New Brunswick. **Sensors**, v. 8, n. 1, p. 412-428, 2008.



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