DOI:10.24850/j-tyca-2018-04-07

Article

Comparison of RDI based on PET in three climatic locations in San Luis Potosi, Mexico

Contraste por *PET* del RDI en tres localidades climáticas de San Luis Potosí, México

Daniel Francisco Campos-Aranda[1]

[1]Retired teacher, Universidad Autónoma de San Luis Potosí, San Luis Potosí, SLP, Mexico, campos_aranda@hotmail.com

Correspondence author: Daniel Francisco Campos-Aranda, campos_aranda@hotmail.com

Abstract

Meteorological droughts are a recurring natural phenomenon that causes lack of precipitation. The *severity* of meteorological droughts is estimated by established algorithms known as *drought indices*. One such procedure, perhaps the simplest, is the *Reconnaissance Drought Index,* or RDI, which is based on the ratio between precipitation and potential evapotranspiration (*PET*) for a determined continuous period of months. In this study, the RDI is applied to three durations of meteorological drought at a weather station selected from each of the three geographic or climate zones in the state of San Luis Potosi, Mexico, which are: Villa de Arriaga (Potosino Plateau), Río Verde (Mean Zone), and Xilitla (Huasteca Region). The monthly rainfall records and average and minimum temperatures of each station cover more than 50 years. *PET* was estimated by four methods: (1) the Penman–Monteith formula, which is the reference method, (2) the Thornthwaite, (3) the Turc, and (4) the Hargreaves–Samani. The operating procedures for these criteria are detailed in appendices. The analysis of the results indicates that the RDIs estimated with the Hargreaves–Samani method are best for reproducing the results of the Penman–Monteith formula, in the three climatic locations processed. The Turc method also led to results similar to those of the reference. Therefore, it can be said that the RDI is a robust drought index, which practically does not depend on the method of estimating the *PET*. There is a noticeable difference in the operational procedures of the Penman–Monteith formula and the Hargreaves–Samani method. The latter is a practical solution that is worth mentioning.

Keywords: Meteorological droughts, potential evapotranspiration, statistical tests, mean square error, mean bias error, types of meteorological drought (light, moderate, severe and extreme).

Resumen

Las *sequías meteorológicas* son un fenómeno natural recurrente que origina una escasez de precipitación. La *severidad* de las sequías meteorológicas se estima a través de algoritmos establecidos, conocidos como *índices de sequías*. Uno de tales procedimientos, quizá el más simple, es el *índice de reconocimiento de sequías* o RDI (Reconnaissance Drought Index), que está basado en el cociente entre la precipitación y evapotranspiración potencial (*ETP*), ocurridas en un cierto lapso, seguido de meses. En este estudio se aplica el RDI en tres duraciones de sequía meteorológica, en cada una de las tres estaciones climatológicas seleccionadas de cada zona geográfica o climática del estado de San Luis Potosí, México, que fueron: Villa de Arriaga (Altiplano Potosino), Río Verde (Zona Media) y Xilitla (Región Huasteca). Los registros mensuales de precipitación y temperaturas media y mínima de cada estación abarcan más de 50 años. La *ETP* se estimó con cuatro métodos: 1) la fórmula de Penman-Monteith, que es el criterio de referencia; los criterios de 2) Thornthwaite; 3) Turc, y 4) Hargreaves-Samani. Los procedimientos operativos de estos criterios se exponen en los apéndices (ver más adelante). El análisis de los resultados indica que los RDI estimados con el método de Hargreaves-Samani es el que mejor reproduce los resultados de la fórmula de Penman-Monteith en las tres localidades climáticas procesadas. También el método de Turc conduce a resultados similares a los de referencia y por ello se puede establecer que el RDI es un índice de sequías robusto, que prácticamente no depende del método de estimación de la *ETP*. Al haber una diferencia notable en los procedimientos operativos de la fórmula de Penman-Monteith y del método de Hargreaves-Samani, este último es una solución práctica muy importante.

Palabras clave: sequías meteorológicas, evapotranspiración potencial, pruebas estadísticas, error cuadrático medio, error de sesgo medio, tipos de sequías meteorológicas (ligeras, moderadas, severas y extremas).

Received: 21/06/2016

Accepted: 24/01/2018

Introduction

The *meteorological drought* is a regional natural phenomenon produced by climate variability, which causes a decrease in the normal precipitation in an area over a significant period of time. For that reason, it has adverse effects on nature and society. The *severity* of meteorological droughts is commonly estimated based on *drought indices*, which vary in complexity, ranging from those using a single climatic variable such as the SPI (Standardized Precipitation Index) to those developing a water-soil balance such as the PDSI (Palmer Drought Severity Index). Hao and Singh (2015) have found that a single variable is not sufficient to characterize droughts, because they are recurring natural phenomena caused by multiple factors. Therefore, they have proposed *multivariate drought indexes*.

The *latent variable* approach allows the development of multivariate indices (Hao & Singh, 2015), consisting of establishing new climatic variables by means of a difference, or quotient, of other variables with widespread physical significance, such as monthly precipitation (*P*) and potential evapotranspiration (*PET*). When *P–PET* difference and the SPI operational algorithm were used, the SPEI was developed (Vicente-Serrano, Beguería, & López-Moreno, 2010) and when the *P/PET* ratio was used, the RDI *Reconnaissance Drought Index* was established, whose operational procedure is quite simple (Tsakiris & Vangelis, 2005; Tsakiris, Tigkas, Vangelis, & Pangalou, 2007; Vangelis, Tigkas, & Tsakiris, 2013).

The *objective* of this study was to present, in detail, the process of calculating the annual RDI, with durations of 3, 6, and 12 months. This procedure is applied to monthly rainfall data and average and minimum temperatures in three localities in the state of San Luis Potosí, representative of its three geographical or climatic zones. For this comparison of the RDI, the *PET* was estimated with four methods, whose detailed description is presented in appendices. These are: (1) the Penman–Monteith formula, which was the reference method; (2) Thornthwaite; (3) Turc, and (4) Hargreaves–Samani. The three results are analyzed and conclusions are formulated.

Methods and materials

The $\mathbf{RDI_{st}}$ equations

The *reconnaissance drought index* (RDI) is initially calculated as the quotient between the accumulated monthly precipitation and the respective potential evapotranspiration, in *k* months considered for each study year *i* (Tsakiris & Vangelis, 2005; Tsakiris *et al.*, 2007; Vangelis *et al.*, 2013; Campos-Aranda, 2014):

$$a_k^i = \frac{\sum_{j=1}^{k} P_j^i}{\sum_{j=1}^{k} ETP_j^i} \quad (1)$$

In the previous equation, *k* is the *duration* of the meteorological drought studied, *j* the month considered, and *i* a range from 1 to *NA*, which is the number of years of the processed records (> 30). Since the magnitudes of a_k^i can be represented probabilistically by the log–normal distribution, the standardized RDI values are easily obtained with the equation:

$$RDI_{st}^i = \frac{y_k^i - \bar{y}}{\sigma_y} \quad (2)$$

in which:

$$y_k^i = \ln\left(a_k^i\right) \quad (3)$$

In Equation (2), $\bar{y}$ is the arithmetic mean and σ_y the standard deviation of the values y_k^i. The positive values of the RDI_{st} indicate wet periods and the negative ones are meteorological droughts, with the following severity: *light* up to −1.00, *moderate* ranging from −1.00 to −1.50, *severe* ranging from −1.50 to −2.00, and lastly, *extreme* less than −2.00. The common durations of *k* are 3, 6, 9, and 12 months, where the first three relate to the months with the highest percentage of precipitation and the fourth to the period from January to December. Durations less than one year may also correspond to the period of crop growth or times of high demand. Campos-Aranda (2014) present a comparison between the RDI_{st} and the SPI.

Estimation of the reference *PET*

Towards the end of the 1970s, the Food and Agriculture Organization of the United Nations (FAO) formulated guidelines for estimating water demands for crops (Doorenbos & Pruit, 1977). Advances in research and more accurate assessments of the use of water by crops show that the Penman method, suggested by the FAO, often overestimates the requirements, and that the alternative empirical criteria presented, in a variable way, closely represent reality (Allen, Pereira, Raes, & Smith, 1998).

In May 1990, FAO organized a panel of experts and researchers, in collaboration with the International Irrigation and Drainage Commission (ICID) and the World Meteorological Organization (WMO), to review the methods for estimating crop demands and establish their modifications. The panel recommended the adoption of the Penman-Monteith formula as the standard method for estimating reference evapotranspiration (*ETo*) and advised on the estimation procedures for its various meteorological parameters (Allen *et al*., 1998).

Appendix 1 presents the Penman-Monteith formula, including the procedures for estimating its parameters based on meteorological data. Appendix 2 describes the FAO recommendations for an application with exclusively climatic data. The latter converts the Penman-Monteith formula into an applicable and valid worldwide method for calculating and comparing *ETo*. Allen *et al*. (1998) indicated that it is preferable to apply the Penman-Monteith formula even with the Appendix 2 approach, rather than use any other empirical method.

Empirical methods for estimating *PET*

In Appendix 3, Equations A.20 to A.31 represent the operational procedures for three empirical methods for estimating potential monthly evapotranspiration (PET_j^i), which are: Thornthwaite, Turc, and Hargreaves–Samani.

Processed climate records

The state of San Luis Potosí can be divided into three climatic regions, which are: Altiplano Potosino Plateau, Mean Zone, and the Huasteca Region. The first has a semi–arid climate, the second is temperate-dry, and the third is warm-humid. In each of these regions, the weather stations with more extensive records and with the least number of missing monthly rainfall data and average and minimum temperatures were searched. The following three were selected: Villa de Arriaga, Río Verde, and Xilitla. In each of them, the few missing rainfall data were considered equal to the mode, estimated based on fitting the mixed gamma distribution to all the available monthly values (Campos-Aranda, 2005a). The missing average and minimum temperatures data were estimated with an interpolation procedure that took into account the trend observed in the month before and after the missing value.

The *average monthly* values of precipitation (mm) and average and minimum temperatures (° C) of each processed weather station are listed in Table 1, as well as their respective recording periods. At the Villa de Arriaga station during the period from 2010 to 2014, average monthly temperatures values were used, due to the fact that the records covered until 2009. Figure 1 shows the location of the three weather stations in the state of San Luis Potosí.

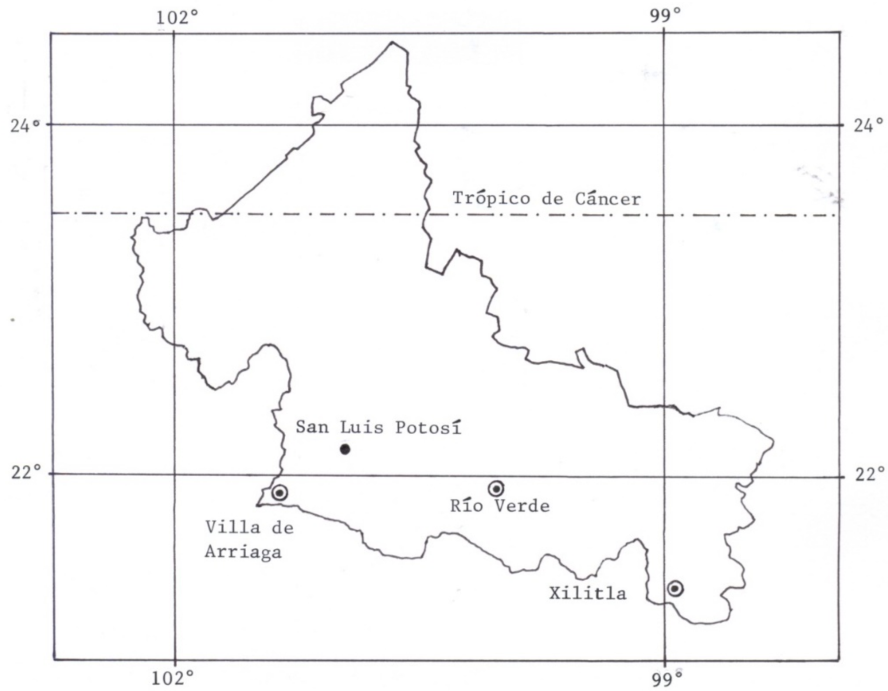

Figure 1. Geographical location of the three weather stations processed of the state of San Luis Potosí, Mexico.

Also, Table 1 shows the monthly average values for solar radiation (*Rs*j), obtained from the maps by Hernández, Tejeda-Martínez and Reyes (1991), on pages 65 to 76, for the three locations of the selected and processed weather stations. Also shown are the magnitudes of the average monthly potential evapotranspiration (mm) (PET_j), obtained through the equations presented in Appendices 1 to 3, applied on a monthly basis.

Table 1. Monthly average values of the climatic elements indicated in the three selected and processed weather stations in the state of San Luis Potosí, Mexico.

Description:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Non	Dec	Annual
Weather station: Villa de Arriaga (Longitude 01° 23' OG. Latitude 21° 54' N. Altitude 2170 masl. NA = 53 years)													

Precipitation (1962–2014)	13.0	7.6	7.0	10.4	30.9	57.2	72.1	56.8	62.7	25.4	5.6	8.9	357.7
Precipitation percentage	3.6	2.1	2.0	2.9	8.6	16.0	20.2	15.9	17.5	7.1	1.6	2.5	100.0
Average temp. (1962–2009)	13.0	13.9	15.9	19.2	20.9	20.8	19.8	19.5	18.8	16.6	14.6	13.4	17.2
Minimum temp. (1962–2009)	4.3	4.9	7.0	9.5	11.2	11.4	11.3	11.0	10.5	8.4	6.0	4.8	8.4
Solar radiation ($cal/cm^2/day$)	400	380	505	650	650	550	520	420	380	450	430	390	480
PET: Penman–Monteith	84.1	87.8	126.5	160.6	177.7	157.1	151.6	133.6	114.3	115.5	97.8	88.7	1495.4
PET: Thornthwaite	37.6	39.3	57.6	82.1	102.3	101.4	98.1	92.9	77.5	60.1	44.7	39.1	832.6
PET: Turc	82.7	75.8	113.5	156.9	162.6	138.8	129.0	105.5	95.2	104.4	94.1	82.1	1340.7
PET: Hargreaves–Samani	87.7	77.4	121.2	166.5	180.1	146.9	139.9	112.0	96.1	110.3	96.0	86.4	1420.5
Weather Station: Río Verde (Longitude 99° 59′ OG. Latitude 21° 56′ N. Altitude 987 masl. NA = 54 years)													
Precipitation (1961–2014)	12.2	10.8	9.4	32.7	36.5	88.7	88.3	71.7	103.4	44.2	15.4	12.9	526.2
Precipitation percentage	2.3	2.0	1.8	6.2	6.9	16.9	16.8	13.6	19.7	8.4	2.9	2.5	100.0
Average temp. (1961–2014)	16.2	18.3	21.7	24.6	26.4	26.1	25.0	25.1	23.9	21.8	19.0	17.0	22.1
Minimum temp. (1961–2014)	8.6	10.0	12.6	15.7	18.2	19.0	18.3	18.3	17.7	15.1	12.1	9.7	14.6
Solar radiation ($cal/cm^2/day$)	375	350	440	550	540	540	530	480	350	390	375	350	430
PET: Penman–Monteith	78.4	87.1	130.6	157.7	170.0	160.5	157.6	148.1	107.5	110.3	93.0	84.7	1485.4
PET: Thornthwaite	36.6	47.5	84.3	119.3	154.2	147.0	135.4	131.3	107.1	82.6	54.3	41.0	1140.6
PET: Turc	88.0	81.2	115.7	149.0	150.5	149.8	145.0	132.6	98.2	104.1	95.0	84.9	1394.1
PET: Hargreaves–Samani	90.8	81.6	124.4	162.1	171.9	165.0	163.1	147.8	101.4	110.5	95.5	86.9	1500.9
Weather station: Xilitla (Longitude 98° 59′ OG. Latitude 21° 23′ N. Altitude 630 masl. NA = 50 years)													

Precipitation (1965–2014)	62.6	65.3	72.5	115.3	175.5	373.9	432.2	429.9	566.1	292.5	101.5	59.0	2746.2
Precipitation percentage	2.3	2.4	2.6	4.2	6.4	13.6	15.8	15.7	20.6	10.7	3.7	2.1	100.0
Average temp. (1965–2014)	17.4	18.7	21.4	24.2	25.9	26.2	25.6	25.9	25.0	23.1	20.3	18.3	22.7
Minimum temp. (1965–2014)	12.6	13.4	15.8	18.5	20.6	21.2	20.9	20.8	20.2	18.1	15.6	13.4	17.6
Solar radiation (cal/cm^2/día)	350	350	400	480	500	460	490	450	310	375	360	300	400
PET: Penman–Monteith	69.1	78.3	106.1	127.9	142.9	132.1	137.9	132.2	98.4	105.9	87.4	74.3	1292.5
PET: Thornthwaite	42.1	48.2	80.2	113.3	146.3	148.9	142.8	142.1	119.1	94.9	62.6	47.2	1187.8
PET: Turc	85.8	82.1	105.8	130.9	139.3	129.8	136.1	126.6	89.9	103.0	94.3	76.8	1300.3
PET: Hargreaves–Samani	87.9	82.5	112.4	140.2	157.2	141.1	152.9	141.3	92.2	110.0	95.1	77.2	1390.0

Quantification of differences with *MSE* and *MBE*

In order to quantify the numerical differences between the annual values of the RDI_{st} of duration *k*, due to the effect of the change in the method of estimating the PET_j^i, the following two statistical indicators were applied: (1) mean square error (*MSE*) and (2) medium bias error (*MBE*); whose expressions are (Vangelis *et al*., 2013):

$$ECM_k = \left[\frac{1}{NA}\sum_{i=1}^{NA}\left(Xref_k^i - Xest_k^i\right)^2\right]^{1/2} \quad (4)$$

$$ESM_k = \frac{1}{NA}\sum_{i=1}^{NA}\left(Xref_k^i - Xest_k^i\right) \quad (5)$$

In the above expressions, $Xref_k^i$ are the annual values of RDI_{st} calculated with Equations (1) to (3), for a duration *k* in months, with the PET_j^i estimated using the Penman-Monteith formula (Appendices 1 and 2), which is the *reference method*, and $Xest_k^i$ are the same annual values as the RDI_{st} but calculated base on PET_j^i, estimated by each one of the three empirical methods presented (Appendix 3). Equations (4) and (5) were also applied to the annual PET^i values (k=12).

Analysis of results

Homogeneity of climatic records

Annual values were obtained based on each completed record of precipitation and monthly average and minimum temperature. With these *series*, the statistical quality analysis of the record was performed, for which the following seven tests were applied, one general and six specific: (1) Von Neumann, which detects loss of randomness by unspecified deterministic components, (2) Anderson and (3) Sneyers, which determine persistence, (4) Kendall and (5) Spearman, which detect trends, (6) Bartlett test of variability, and (7) Cramer, to identify changes in the mean. In all tests, a level of significance (α) of 5% was used. The statistical tests cited can be found in WMO (1971) and Machiwal and Jha (2012). The results of these tests are shown in Table 2, where NH and H represent non–homogeneous and homogeneous series or records, respectively.

Regarding the annual precipitation (*P*), the records from Villa de Arriaga and Río Verde showed persistence, which was also detected with the von Neumann test. When taking into account that persistence is a statistical component of the time series, analyses aimed at quantifying meteorological droughts can continue, since the three records show no trend or changes in the mean, that is, loss of homogeneity.

Table 2. Results of statistical tests applied to annual records of precipitation (*P*) and average (*Tt*) and minimum (*t*) temperatures from the weather stations studied.

Statistical tests:	Villa de Arriaga			Río Verde			Xilitla		
	P	*Tt*	*t*	*P*	*Tt*	*t*	*P*	*Tt*	*t*
1. Von Neumann	NH	NH	NH	NH	NH	NH	H	NH	NH
2. Persistence (Anderson)	NH	NH	NH	NH	NH	NH	H	NH	NH
3. Persistence (Sneyers)	NH	NH	NH	NH	NH	NH	H	NH	NH

4. Trend (Kendall)	H	NH↑	H	H	NH↑	NH↑	H	NH↑	H
5. Trend (Spearman)	H	NH↑	H	H	NH↑	NH↑	H	NH↑	H
6. Variability (Bartlett)	H	NH	NH	H	H	H	H	H	H
7. Change in the mean (Cramer)	H	NH	H	H	NH	NH	H	NH	NH
First-order linear correlation coef. 1 (r_1)	0.523	0.791	0.494	0.285	0.446	0.418	0.049	0.522	0.470

The opposite occurred with annual average temperature (*Tt*) records, which were totally non–homogeneous, since they presented persistence (associated with r_1), an upward trend, and a change in the mean. In relation to the minimum annual temperature (*t*) records, the Rio Verde station was the least homogeneous, since it had an upward trend, and Villa de Arriaga was the most homogeneous, since it only had persistence. Xilitla was also non-homogeneous, having persistence and a change in the mean.

Numerical results of RDI_{st}

Based on the percentages of monthly precipitation shown in Table 1, the three-month period with more rain from July to September and the six–month period from May to October were defined. At Villa de Arriaga, Río Verde, and Xilitla, for *k* = 3 months the sums of percentages varied by 52% and for *k* = 6 months they varied by 83%. Once these periods were defined, Equations 1 to 3 were applied to the precipitation data and to the estimates of the *PET*. Due to space limitations, only some of these results are shown in Tables 3 to 5.

Table 3. Data, RDI_{st} values, and types of annual meteorological droughts (*TS*) calculated with the estimated potential evapotranspiration, according to the empirical criteria indicated, in the Villa de Arriaga weather station, San Luis Potosí

Year	P^i (mm)	According to Penman–Monteith formula							According to Hargreaves–Samani method						
		PET^i (mm)	*k* = 3 months		*k* = 6 months		*k* = 12 months		PET^i (mm)	*k* = 3 months		*k* = 6 months		*k* = 12 months	
			RDI_{st}	TS	RDI_{st}	TS	RDI_{st}	TS		RDI_{st}	TS	RDI_{st}	TS	RDI_{st}	TS
1962	268.4	1495.8	–0.110	SL	–0.169	SL	–0.217	SL	1433.6	–0.112	SL	–0.179	SL	–0.229	SL
1963	279.1	1442.0	–0.444	SL	–0.755	SL	–0.089	SL	1387.2	–0.474	SL	–0.786	SL	–0.108	SL
1964	489.0	1392.8	0.600	–	0.960	–	0.917	–	1370.2	0.553	–	0.889	–	0.855	–

1965	426.1	1376.3	0.600	–	0.389	–	0.704	–	1364.0	0.551	–	0.306	–	0.632	–
1966	631.7	1293.4	0.5714	–	1.264	–	1.475	–	1287.1	0.491	–	1.165	–	1.391	–
1967	538.0	1299.7	0.722	–	0.991	–	1.195	–	1275.1	0.668	–	0.913	–	1.137	–
1968	379.9	1368.5	0.664	–	0.584	–	0.520	–	1347.8	0.595	–	0.500	–	0.459	–
1969	174.0	1450.0	–0.285	SL	–0.786	SL	–0.897	SL	1405.9	–0.331	SL	–0.841	SL	–0.924	SL
1970	269.7	1418.5	–0.078	SL	0.045	–	–0.119	SL	1381.9	–0.133	SL	–0.009	SL	–0.159	SL
1971	593.0	1394.1	1.259	–	1.577	–	1.241	–	1372.1	1.191	–	1.489	–	1.177	–
1972	347.0	1417.3	0.248	–	0.603	–	0.308	–	1388.5	0.194	–	0.533	–	0.257	–
1973	328.5	1418.9	0.647	–	0.538	–	0.213	–	1390.9	0.586	–	0.458	–	0.162	–
1974	156.9	1423.4	0.021	–	–0.978	SL	–1.041	SM	1391.7	–0.031	SL	–1.044	SM	–1.081	SM
1975	280.5	1432.3	0.329	–	0.185	–	–0.069	SL	1397.9	0.267	–	0.118	–	–0.112	SL
1976	359.5	1397.9	0.695	–	0.741	–	0.391	–	1362.3	0.638	–	0.669	–	0.348	–
1977	96.0	1395.6	–0.319	SL	–1.535	SS	–1.837	SS	1353.3	–0.338	SL	–1.567	SS	–1.860	SS
1978	507.5	1363.3	1.321	–	1.333	–	1.016	–	1325.2	1.288	–	1.273	–	0.974	–
1979	192.0	1419.7	0.077	–	–0.770	SL	–0.695	SL	1372.7	0.051	–	–0.805	SL	–0.719	SL
1980	375.5	1393.4	0.064	–	–0.062	SL	0.470	–	1355.5	0.039	–	–0.101	SL	0.430	–
1981	270.9	1385.6	–0.567	SL	–0.343	SL	–0.072	SL	1340.1	–0.577	SL	–0.367	SL	–0.100	SL
1982	292.5	1438.5	–0.443	SL	–0.015	SL	–0.006	SL	1376.0	–0.449	SL	–0.024	SL	–0.015	SL
1983	154.5	1385.6	–0.219	SL	–0.791	SL	–1.021	SM	1345.3	–0.232	SL	–0.804	SL	–1.050	SM

1984	148.0	1419.9	–0.017	SL	–1.055	SM	–1.135	SM	1372.2	–0.059	SL	–1.090	SM	–1.156	SM
1985	167.0	1428.0	–0.765	SL	–0.792	SL	–0.941	SL	1369.2	–0.760	SL	–0.789	SL	–0.949	SL
1986	504.0	1404.8	–0.621	SL	1.012	–	0.953	–	1371.9	–0.638	SL	0.978	–	0.904	–
1987	504.9	1377.7	0.939	–	1.049	–	0.989	–	1321.5	0.947	–	1.056	–	0.970	–
1988	256.0	1407.2	0.337	–	0.054	–	–0.194	SL	1343.9	0.338	–	0.51	–	–0.200	SL
1989	359.5	1469.2	–0.052	SL	–0.155	SL	0.307	–	1354.1	0.018	–	–0.074	SL	0.358	–
1990	728.3	1507.6	0.916	–	1.440	–	1.456	–	1384.9	0.989	–	1.518	–	1.507	–
1991	1028.5	1564.4	1.572	–	2.045	–	1.977	–	1416.6	1.649	–	2.138	–	2.049	–
1992	838.0	1624.5	0.015	–	0.934	–	1.567	–	1458.3	0.115	–	1.051	–	1.656	–
1993	523.0	1716.8	0.696	–	0.754	–	0.677	–	1639.7	0.634	–	0.690	–	0.667	–
1994	564.9	1561.4	0.632	–	1.123	–	0.968	–	1448.4	0.706	–	1.191	–	1.005	–
1995	392.8	1530.0	–0.103	SL	–0.190	SL	0.388	–	1409.2	–0.042	SL	–0.115	SL	0.440	–
1996	666.0	1686.9	1.263	–	1.136	–	1.115	–	1506.8	1.370	–	1.260	–	1.215	–
1997	454.0	1730.8	–0.052	SL	0.272	–	0.424	–	1536.6	0.043	–	0.393	–	0.538	–
1998	418.0	1748.9	0.181	–	0.383	–	0.267	–	1564.4	0.285	–	0.504	–	0.369	–
1999	249.0	1698.0	–0.126	SL	–0.256	SL	–0.558	SL	1516.1	–0.065	SL	–0.153	SL	–0.449	SL
2000	123.0	1599.0	–5.157	SE	–1.464	SM	–1.648	SS	1469.4	–5.148	SE	–1.411	SM	–1.582	SS
2001	111.8	1564.2	–0.470	SL	–1.484	SM	–1.773	SS	1458.5	–0.452	SL	–1.438	SM	–1.730	SS
2002	139.3	1582.7	–0.956	SL	–1.437	SM	–1.421	SM	1516.8	–0.956	SL	–1.419	SM	–1.426	SM

2003	337.0	1638.4	0.463	–	0.356	–	0.014	–	1590.3	0.455	–	0.343	–	–0.021	SL
2004	613.4	1645.2	0.452	–	0.978	–	1.019	–	1532.7	0.481	–	1.017	–	1.048	–
2005	287.0	1667.3	0.147	–	–0.323	SL	–0.287	SL	1548.7	0.195	–	–0.262	SL	–0.246	SL
2006	340.0	1637.5	0.120	–	0.121	–	0.029	–	1531.1	0.152	–	0.158	–	0.058	–
2007	270.0	1630.7	–0.564	SL	–0.473	SL	–0.353	SL	1531.0	–0.537	SL	–0.439	SL	–0.329	SL
2008	546.4	1602.8	1.214	–	1.177	–	0.867	–	1499.5	1.247	–	1.207	–	0.890	–
2009	201.0	1518.3	–0.501	SL	–0.627	SL	–0.731	SL	1468.8	–0.497	SL	–0.618	SL	–0.755	SL
2010	264.0	1498.3	0.029	–	–0.763	SL	–0.248	SL	1420.1	0.036	–	–0.753	SL	–0.241	SL
2011	75.8	1498.3	–1.324	SM	–2.076	SE	–2.357	SE	1420.1	–1.323	SM	–2.065	SE	–2.338	SE
2012	134.9	1498.3	–0.669	SL	–1.610	SS	–1.382	SM	1420.1	–0.665	SL	–1.599	SS	–1.369	SM
2013	138.9	1498.3	–1.436	SM	–1.849	SS	–1.333	SM	1420.1	–1.436	SM	–1.838	SS	–1.320	SM
2014	165.0	1498.3	–1.518	SS	–1.287	SM	–1.043	SM	1420.1	–1.517	SS	–1.276	SM	–1.030	SM

Table 4. Data, RDI_{st} values and types of annual meteorological droughts (*TS*) calculated with the estimated potential evapotranspiration, according to the indicated empirical criteria, in the Villa de Arriaga weather station, San Luis Potosí

Year	Tt^i (°C)	t^i (°C)	According to Thornthwaite criterion							According to Turc criterion						
			PET^i (mm)	*k* = 3 months		*k* = 6 months		*k* = 12 months		PET^i (mm)	*k* = 3 months		*k* = 6 months		*k* = 12 months	
				RDI_{st}	TS	RDI_{st}	TS	RDI_{st}	TS		RDI_{st}	TS	RDI_{st}	TS	RDI_{st}	TS
1962	17.4	9.0	825.3	–0.122	SL	–0.203	SL	–0.215	SL	1354.2	–0.112	SL	–0.175	SL	–0.228	SL
1963	16.5	8.3	776.	–0.383	SL	–0.702	SL	–0.045	SL	1319.6	–0.485	SL	–0.799	SL	–0.120	SL
1964	16.2	9.0	758.4	0.644	–	1.107	–	0.946	–	1309.5	0.538	–	0.859	–	0.830	–

1965	15.9	8.9	756.8	0.623	−	0.416	−	0.716	−	1298.7	0.537	−	0.285	−	0.614	−
1966	14.0	7.5	700.3	0.630	−	1.335	−	1.515	−	1217.5	0.476	−	1.137	−	1.379	−
1967	13.7	6.6	693.0	0.766	−	1.089	−	1.260	−	1206.2	0.651	−	0.886	−	1.126	−
1968	15.5	8.3	742.8	0.709	−	0.639	−	0.553	−	1282.4	0.579	−	0.480	−	0.443	−
1969	16.8	8.8	798.5	−0.301	SL	0.852	SL	0.894	SL	1330.8	−0.334	SL	−0.840	SL	−0.923	SL
1970	16.2	8.5	772.4	−0.086	SL	0.071	−	−0.094	SL	1312.1	−0.143	SL	−0.026	SL	−0.167	SL
1971	16.1	8.8	760.1	1.310	−	1.658	−	1.269	−	1309.9	1.172	−	1.460	−	1.151	−
1972	16.4	8.9	774.1	0.284	−	0.664	−	0.329	−	1321.0	0.181	−	0.511	−	0.242	−
1973	16.5	9.0	778.0	0.669	−	0.555	−	0.228	−	1323.0	0.571	−	0.438	−	0.148	−
1974	16.6	9.0	780.5	0.002	−	−0.981	SL	−1.031	SM	1325.1	−0.039	SL	−1.050	SM	1.088	SM
1975	16.6	9.0	780.2	0.423	−	0.271	−	−0.045	SL	1331.4	0.251	−	0.101	−	−0.126	SL
1976	15.9	8.3	751.8	0.765	−	0.848	−	0.439	−	1300.8	0.620	−	0.642	−	0.327	−
1977	15.6	7.9	747.4	−0.257	SL	−1.475	SM	1.790	SS	1288.2	−0.351	SL	−1.578	SS	1.861	SS
1978	14.9	7.3	727.8	1.365	−	1.428	−	1.078	−	1259.3	1.270	−	1.244	−	0.957	−
1979	16.0	8.2	768.0	0.92	−	−0.741	SL	−0.661	SL	1301.9	0.044	−	−0.814	SL	−0.722	SL
1980	15.7	8.2	754.5	0.053	−	−0.054	SL	0.507	−	1287.1	0.29	−	−0.117	SL	0.417	−
1981	15.4	7.6	737.9	−0.503	SL	−0.253	SL	−0.009	SL	1276.0	−0.589	SL	−0.388	SL	−0.113	SL
1982	16.1	7.9	766.2	−0.371	SL	0.067	−	0.057	−	1308.4	−0.460	SL	−0.041	SL	−0.027	SL
1983	15.4	7.7	739.9	−0.089	SL	−0.676	SL	−0.966	SL	1279.0	−0.248	SL	−0.816	SL	−1.055	SM

1984	16.1	8.2	762.0	0.043	–	–0.968	SL	–1.089	SM	1307.6	–0.073	SL	–1.103	SM	–1.164	SM
1985	16.0	7.8	764.1	–0.724	SL	–0.754	SL	–0.889	SL	1301.6	–0.766	SL	–0.798	SL	–0.954	SL
1986	16.2	8.8	767.6	–0.627	SL	1.052	–	0.977	–	1303.5	–0.644	SL	0.959	–	0.888	–
1987	14.8	6.8	732.4	0.944	–	1.084	–	1.059	–	1244.7	0.933	–	1.034		0.968	–
1988	15.2	6.9	745.8	0.364	–	0.088	–	–0.123	SL	1269.2	0.327	–	0.039	–	–0.199	SL
1989	15.6	5.9	755.8	–0.014	SL	–0.056	SL	0.430	–	1281.7	0.012	–	–0.084	SL	0.352	–
1990	16.2	6.1	790.6	0.926	–	1.472	–	1.551	–	1299.8	0.985	–	1.509	–	1.507	–
1991	16.9	5.7	821.0	1.621	–	2.085	–	2.072	–	1327.5	1.645	–	2.137	–	2.048	–
1992	17.9	6.2	881.9	–0.092	SL	0.855	–	1.603	–	1362.0	0.142	–	1.073	–	1.663	–
1993	22.2	12.8	1603.7	–0.379	SL	–0.588	SL	0.210	SL	1454.2	0.786	–	0.845	–	0.767	–
1994	17.6	7.6	872.3	0.564	–	0.977	–	0.953	–	1345.72	0.722	–	1.216	–	1.025	–
1995	16.5	6.3	821.4	–0.002	SL	–0.260	SL	0.439	–	1306.3	–0.044	SL	–0.079	SL	0.468	–
1996	19.2	6.9	981.5	1.126	–	0.837	–	1.032	–	1387.1	1.401	–	1.315	–	1.249	–
1997	19.9	7.0	996.7	–0.242	SL	0.41	–	0.356	–	1429.4	0.874	–	0.443	–	0.559	–
1998	20.7	8.3	1055.0	–0.112	SL	0.056	–	0.120	–	1451.1	0.341	–	0.561	–	0.396	–
1999	19.3	6.7	923.3	–0.060	SL	–0.234	SL	0.532	SL	1420.8	–0.061	SL	–0.132	SL	–0.434	SL
2000	18.3	7.7	854.6	–5.144	SE	–1.385	SM	–1.597	SS	1389.3	–5.133	SE	–1.402	SM	–1.574	SS
2001	18.1	8.2	845.1	–0.407	SL	–1.446	SM	–1.740	SS	1380.1	–0.456	SL	–1.430	SM	–1.722	SS
2002	19.6	10.7	912.0	–0.920	SL	–1.422	SM	–1.496	SM	1429.5	–0.952	SL	–1.402	SM	–1.414	SM

2003	21.5	13.1	1019.0	0.488	–	0.346	–	–0.186	SL	1486.5	0.461	–	0.359	–	–0.004	SL
2004	20.2	10.1	927.9	0.555	–	1.148	–	0.988	–	1446.7	0.481	–	1.011	–	1.042	–
2005	20.6	10.3	951.2	0.234	–	–0.182	SL	–0.342	SL	1458.5	0.198	–	–0.258	SL	–0.240	SL
2006	20.2	10.3	924.2	0.228	–	0.286	–	–0.006	SL	1446.0	0.151	–	0.155	–	0.057	–
2007	20.2	10.5	925.3	–0.485	SL	–0.350	SL	–0.399	SL	1446.0	–0.534	SL	–0.436	SL	–0.328	SL
2008	19.3	9.8	901.2	1.289	–	1.278	–	0.841	–	1409.1	1.244	–	1.199	–	0.893	–
2009	18.4	10.2	861.4	–0.498	SL	–0.606	SL	–0.778	SL	1386.1	–0.496	SL	–0.616	SL	–0.750	SL
2010	17.2	8.4	808.6	0.047	–	–0.745	SL	–0.208	SL	1348.4	0.031	–	–0.755	SL	–0.249	SL
2011	17.2	8.4	808.6	–1.326	SM	–2.083	SE	–2.324	SE	1348.4	–1.323	SM	–2.057	SE	–2.332	SE
2012	17.2	8.4	808.6	–0.661	SL	–1.608	SS	–1.324	SM	1348.4	–0.668	SL	–1.595	SS	–1.370	SM
2013	17.2	8.4	808.6	–1.440	SM	–1.852	SS	–1.297	SM	1348.4	–1.435	SM	–1.832	SS	–1.321	SM
2014	17.2	8.4	808.6	–1.523	SS	–1.279	SM	–1.005	SM	1348.4	–1.517	SS	–1.274	SM	–1.033	SM

Table 5. Data, RDI_{st} values and types of annual meteorological droughts (*TS*) calculated with the estimated potential evapotranspiration according to the indicated empirical criteria, in the Xilitla weather station, San Luis Potosí

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Year	P^i (mm)	According to Penman–Monteith formula							According to Turc method						
		PET^i (mm)	*k* = 3 months		*k* = 6 months		*k* = 12 months		PET^i (mm)	*k* = 3 months		*k* = 6 months		*k* = 12 months	
			RDI_{st}	TS	RDI_{st}	TS	RDI_{st}	TS		RDI_{st}	TS	RDI_{st}	TS	RDI_{st}	TS
1965	3010.6	1248.6	0.755	–	0.616	–	0.606	–	1293.6	0.692	–	0.517	–	0.522	–
1966	2627.7	1228.8	–2.209	SE	–0.106	SL	0.123	–	1272.7	–2.311	SE	–0.214	SL	0.009	–
1967	2912.1	1280.6	0.640	–	0.446	–	0.370	–	1290.1	0.600	–	0.501	–	0.391	–

1968	2302.7	1268.2	0.410	–	–0.288	SL	–0.536	SL	1289.1	0.348	–	–0.345	SL	–0.612	SL
1969	3532.0	1285.4	1.448	–	1.102	–	1.133	–	1301.0	1.504	–	1.172	–	1.182	–
1970	2961.0	1244.1	0.227	–	0.779	–	0.554	–	1273.4	0.189	–	0.758	–	0.518	–
1971	3330.5	1301.2	0.749	–	0.945	–	0.847	–	1300.9	0.730	–	0.951	–	0.931	–
1972	3202.0	1238.5	0.072	–	0.771	–	0.888	–	1292.6	–0.011	SL	0.639	–	0.789	–
1973	3166.0	1215.6	0.276	–	1.054	–	0.917	–	1290.1	0.121	–	0.911	–	0.749	–
1974	3044.9	1247.6	0.865	–	0.710	–	0.655	–	1290.9	0.754	–	0.579	–	0.579	–
1975	3474.5	1294.7	1.304	–	1.183	–	1.038	–	1294.0	1.510	–	1.377	–	1.135	–
1976	3297.2	1167.0	1.073	–	1.014	–	1.245	–	1263.1	0.948	–	0.828	–	1.014	–
1977	1787.2	1255.0	–1.913	SS	–1.601	SS	–1.516	SS	1285.5	–2.008	SE	–1.656	SS	–1.686	SS
1978	3276.6	1234.0	0.781	–	0.909	–	0.995	–	1287.7	0.761	–	0.886	–	0.904	–
1979	2364.1	1326.2	–0.111	SL	–0.692	SL	–0.611	SL	1297.6	–0.025	SL	–0.622	SL	–0.527	SL
1980	1896.6	1363.4	–0.617	SL	–1.790	SS	–1.610	SS	1314.2	–0.444	SL	–14.704	SS	–1.527	SS
1981	3351.7	1307.4	0.183	–	0.627	–	0.853	–	1304.6	0.249	–	0.713	–	0.946	–
1982	1951.0	1345.8	–1.812	SS	–1.770	SS	–1.444	SM	1310.0	–1.667	SS	–1.752	SS	–1.392	SM
1983	3728.5	1320.8	1.790	–	1.391	–	1.242	–	1296.7	1.909	–	1.561	–	1.428	–
1984	3758.7	1257.0	1.473	–	1.720	–	1.474	–	1287.5	1.400	–	1.718	–	1.493	–
1985	2720.6	1296.9	–0.449	SL	–0.179	SL	0.045	–	1294.7	–0.482	SL	–0.222	SL	0.084	–
1986	2552.2	1284.9	–1.433	SM	–0.244	SL	–0.175	SL	1299.3	–1.449	SM	–0.299	SL	–0.205	SL

1987	2388.8	1257.9	0.319	–	0.076	SL	–0.356	SL	1272.9	0.310	–	–0.097	SL	–0.401	SL
1988	2815.8	1253.0	–0.167	SL	0.227	–	0.323	–	1288.9	–0.198	SL	0.123	–	0.251	–
1989	2713.6	1333.0	–0.386	SL	–0.850	SL	–0.076	SL	1303.6	–0.423	SL	–0.859	SL	0.044	–
1990	2639.0	1285.6	0.290	–	–0.231	SL	–0.042	SL	1302.9	0.232	–	–0.291	SL	–0.074	SL
1991	3597.0	1256.3	0.853	–	1.196	–	1.299	–	1301.9	0.779	–	1.194	–	1.257	–
1992	3175.5	1191.0	0.320	–	0.585	–	1.012	–	1279.9	0.236	–	0.451	–	0.796	–
1993	3481.9	1240.3	0.557	–	1.010	–	1.219	–	1296.0	0.477	–	0.922	–	1.137	–
1994	2532.3	1271.3	0.333	–	0.029	–	–0.164	SL	1305.9	0.351	–	–0.019	SL	–0.260	SL
1995	2617.0	1292.1	0.362	–	0.002	–	–0.096	SL	1313.3	0.356	–	0.009	–	–0.143	SL
1996	1918.0	1305.1	–0.695	SL	–1.086	SM	–1.389	SM	1304.4	–0.713	SL	–1.107	SM	–1.446	SM
1997	1999.5	1273.9	–2.126	SE	–1.269	SM	–1.123	SM	1302.9	–2.156	SE	–1.344	SM	–1.263	SM
1998	2819.5	1314.2	0.567	–	0.155	–	0.136	–	1326.8	0.572	–	0.201	–	0.132	–
1999	2576.1	1312.0	0.729	–	0.188	–	–0.221	SL	1313.4	0.710	–	0.198	–	–0.211	SL
2000	1974.6	1307.4	–1.860	SS	–1.214	SM	–1.279	SM	1317.6	–1.898	SS	–1.309	SM	–1.365	SM
2001	2751.0	1293.4	–0.158	SL	–0.053	SL	0.101	–	1313.9	–0.161	SL	–0.059	SL	0.069	–
2002	1880.7	1314.4	–0.902	SL	–1.040	SM	–1.497	SM	1309.7	–0.888	SL	–0.996	SL	–1.548	SS
2003	2686.6	1294.2	0.557	–	0.204	–	0.003	–	1305.0	0.448	–	0.187	–	–0.004	SL
2004	2155.8	1283.1	–0.754	SL	–0.967	SL	–0.849	SL	1301.5	–0.761	SL	–1.041	SM	–0.936	SL
2005	2517.9	1332.2	–0.601	SL	–0.152	SL	–0.375	SL	1316.0	–0.507	SL	–0.076	SL	–0.318	SL

2006	1654.4	1379.0	–1.443	SM	–2.448	SE	–2.206	SE	1322.8	–1.378	SM	–2.422	SE	–2.140	SE
2007	2948.9	1311.1	0.420	–	0.410	–	0.326	–	1305.6	0.486	–	0.499	–	0.394	–
2008	3475.2	1332.7	0.943	–	1.143	–	0.922	–	1310.1	0.940	–	1.247	–	1.083	–
2009	2239.0	1393.9	–0.892	SL	–0.887	SL	–1.030	SM	1325.3	–0.714	SL	–0.688	SL	–0.851	SL
2010	2880.7	1340.4	0.710	–	–0.016	SL	0.143	–	1302.2	0.805	–	0.102	–	0.304	–
2011	1554.5	1387.8	–1.169	SM	–2.122	SE	–2.483	SE	1313.4	–1.107	SM	–2.045	SE	–2.376	SE
2012	2202.8	1376.5	–0.193	SL	–0.987	SL	–1.046	SM	1315.2	–0.108	SL	–0.905	SL	–0.888	SL
2013	3764.8	1327.5	1.333	–	1.186	–	1.260	–	1304.0	1.410	–	1.297	–	1.446	–
2014	3100.4	1356.1	–0.452	SL	0.464	–	0.392	–	1311.7	–0.418	SL	0.530	–	0.588	–

Tables 3 and 4 show all the results of the Villa de Arriaga station, which is the one with the greatest variability, since its average annual precipitation and temperature ranged from 75.8 to 1 028.5 mm and from 13.7 to 21.5 °C. Table 5 shows some of the results corresponding to the Xilitla station, which is the one with less dispersion, with average annual precipitation and temperature ranging from 1 554.5 to 3 764.8 mm and from 21.2 to 23.9 °C, respectively.

Tables 3 to 5 use the following symbols for the severity or types of meteorological drought: light droughts (SL), moderate droughts (SM), severe droughts (SS), and extreme droughts (SE). The numerical results of the RDI_{st} shown in Tables 3 to 5 allow a precise or detailed inspection and comparison of their annual values, observing a remarkable similarity both in their annual values and in the types of meteorological droughts they define, independently of the PET estimation method. The above will be numerically modified in Tables 6 and 7, and can be seen in Figure 2 with the results in Table 3, relating to the Villa de Arriaga station, with *k* = 12 months.

Table 6. Comparison of the *MSE* and the *MBE* between the annual *PET* and RDIst with the Penman-Monteith formula and their respective values as estimated with the three empirical methods cited, for the three indicated weather stations in the state of San Luis Potosí, Mexico. Note: minimum values of each comparison are shown in parenthesis.

	Station: Villa de Arriaga	Station: Río Verde	Station: Xilitla

Concept:	*k* =3	*k*= 6	*k* = 12	*k* =3	*k*= 6	*k* = 12	*k* =3	*k*= 6	*k* = 12
MSE of *PET* annual de Thornthwaite	–	–	668.3	–	–	346.4	–	–	110.8
MSE of *PET* annual de Turc	–	–	166.8	–	–	94.2	–	–	(39.1)
MSE of *PET* annual de Hargreaves–Samani	–	–	(89.1)	–	–	(24.5)	–	–	103.1
MBE of *PET* annual de Thornthwaite	–	–	662.8	–	–	344.8	–	–	104.8
MBE of *PET* annual de Turc	–	–	154.7	–	–	91.3	–	–	(–7.8)
MBE of *PET* annual de Hargreaves–Samani	–	–	(74.9)	–	–	(–15.5)	–	–	–97.5
MSE of RDI_{st} annuales de Thornthwaite	0.165	0.210	0.136	0.072	0.100	0.097	0.086	0.117	0.112
MSE of RDI_{st} annuales de Turc	0.062	0.080	0.062	0.035	0.044	0.046	0.082	0.089	0.108
MSE of RDI_{st} annuales de Hargreaves–Samani	(0.050)	(0.062)	(0.050)	(0.029)	(0.036)	(0.039)	(0.070)	(0.076)	(0.098)
MBE of RDI_{st} annuales de Thornthwaite	$(-0.263\cdot10^{-7})$	$3.104\cdot10^{-7}$	$(-0.157\cdot10^{-7})$	$0.464\cdot10^{-7}$	$(-0.072\cdot10^{-7})$	$2.390\cdot10^{-7}$	$(-1.571\cdot10^{-7})$	$10.82\cdot10^{-7}$	$-3.034\cdot10^{-7}$
MBE of RDI_{st} annuales de Turc	$-1.468\cdot10^{-7}$	$2.525\cdot10^{-7}$	$-1.338\cdot10^{-7}$	$-3.024\cdot10^{-7}$	$1.352\cdot10^{-7}$	$-4.136\cdot10^{-7}$	$4.908\cdot10^{-7}$	$-3.648\cdot10^{-7}$	$(-2.730\cdot10^{-7})$
MBE of RDI_{st} annuales de Hargreaves–Samani	$-0.461\cdot10^{-7}$	$(-1.091\cdot10^{-7})$	$1.343\cdot10^{-7}$	$(-0.248\cdot10^{-7})$	$-5.061\cdot10^{-7}$	$(1.209\cdot10^{-7})$	$8.440\cdot10^{-7}$	$(0.071\cdot10^{-7})$	$-4.518\cdot10^{-7}$

Table 7. Severity of the meteorological droughts obtained with the RDI_{st} for the three durations (*k*) studied, in months, applying each one of the estimation *PET* criteria, in the three weather stations indicated, in the state of San Luis Potosí, Mexico.

Types of meteorological droughts (SMET):	Penman–Monteith						Thornthwaite						Turc						Hargreaves–Samani					
	k =3		*k*= 6		*k* = 12		*k* =3		*k*= 6		*k* = 12		*k* =3		*k*= 6		*k* = 12		*k* =3		*k*= 6		*k* = 12	
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
Weather Station: Villa de Arriaga (NA/2 = 26.5)																								

Light SMET	20	83.3	17	65.4	15	57.7	22	84.6	18	69.2	18	64.3	19	82.6	17	63.0	16	59.3	19	82.6	17	63.0	16	59.3
Moderate SMET	2	8.3	5	19.2	7	26.9	2	7.7	5	19.2	6	21.4	2	8.7	6	22.2	7	25.9	2	8.7	6	22.2	7	25.9
Severe SMET	1	4.2	3	11.5	3	11.5	1	3.8	2	7.7	3	10.7	1	4.3	3	11.1	3	11.1	1	4.3	3	11.1	3	11.1
Extreme SMET	1	4.2	1	3.8	1	3.8	1	3.8	1	3.8	1	3.6	1	4.3	1	3.7	1	3.7	1	4.3	1	3.7	1	3.7
Weather Station: Río Verde (NA/2 = 27)																								
Light SMET	17	68.0	22	78.6	18	66.7	18	69.2	19	70.4	19	67.9	18	69.2	22	78.6	18	66.7	18	69.2	22	78.6	18	66.7
Moderate SMET	4	16.0	4	14.3	6	22.2	6	23.1	6	22.2	6	21.4	6	23.1	4	14.3	6	22.2	6	23.1	4	14.3	6	22.2
Severe SMET	2	8.0	0	0.0	2	7.4	0	0.0	1	3.7	2	7.1	0	0.0	1	3.6	2	7.4	0	0.0	1	3.6	2	7.4
Extreme SMET	2	8.0	2	7.1	1	3.7	2	7.7	1	3.7	1	3.6	2	7.7	1	3.6	1	3.7	2	7.7	1	3.6	1	3.7
Weather Station: Xilitla (NA/2 = 25)																								
Light SMET	13	61.9	14	60.9	11	50.0	12	57.1	15	60.0	14	58.3	14	63.6	14	60.9	13	59.1	13	61.9	14	58.3	13	59.1
Moderate SMET	3	14.3	4	17.4	7	31.8	4	19.0	6	24.0	6	25.0	3	13.6	4	17.4	4	18.2	3	14.3	5	20.8	4	18.2
Severe SMET	3	14.3	3	13.0	2	9.1	3	14.3	3	12.0	2	8.3	2	9.1	3	13.0	3	13.6	2	9.5	3	12.5	3	13.6
Extreme SMET	2	9.5	2	8.7	2	9.1	2	9.5	1	4.0	2	8.3	3	13.6	2	8.7	2	9.1	3	14.3	2	8.3	2	9.1

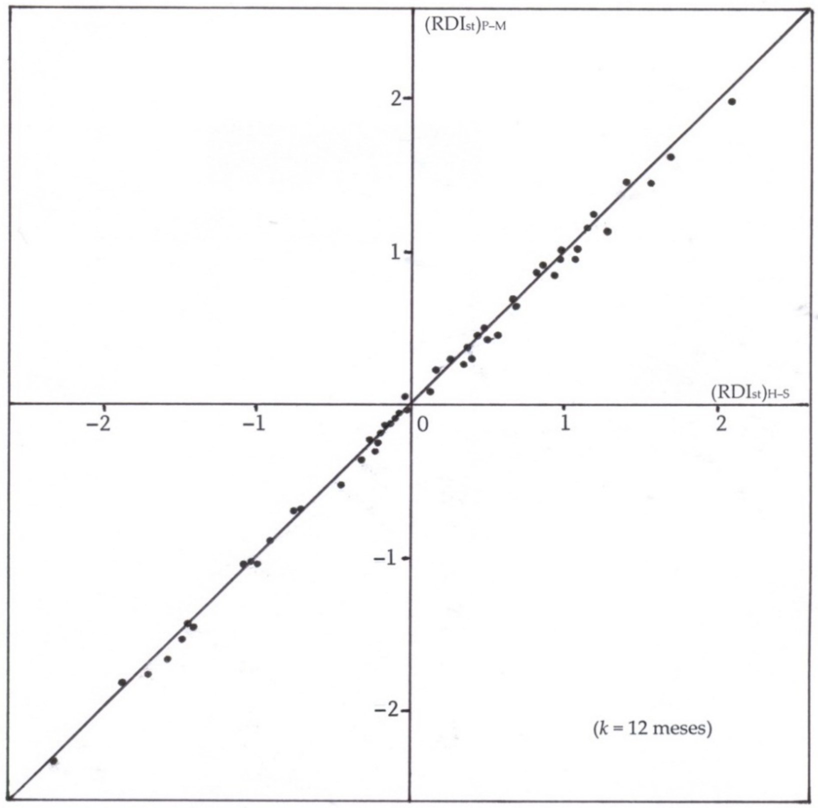

Figura 2. Comparison of the 53 RDI_{st} values calculated with the *PET* based on Penman–Monteith (ordinate) and Hargreaves–Samani (abscissa), in the Villa de Arriaga weather station, San Luis Potosí

Results of *MSE* and *MBE*

Table 6 shows the numerical values of the *MSE* and the *MBE*. The comparison at the annual level of the *PET* estimates indicates that, in semi–arid and temperate–dry climates, the results of the Thornthwaite method is least similar to the Penman–Monteith formula, and the Hargreaves–Samani is more accurate. In the warm–humid climate, the results from the above two methods are nearly the same, and the Turc is most accurate. The minus sign in the *MBE* corresponding to the Turc and Hargreaves–Samani methods (last column of Table 6) indicates that these criteria overestimated the *PET*, with respect to that of the reference. The previous findings define the presentation of the results of the RDI_{st} in Table 3, Table 4, and Table 5.

The *MSE* corresponding to the annual RDI_{st} values for the three durations analyzed was greater with the Thornthwaite method and of similar order of magnitude with the other two criteria, but the Hargreaves–Samani method always led to a lower value for the three climates studied. Regarding the *MBE* values obtained, in general they were low, of the same order of magnitude and modifying the results of the *MBE*, varying their sign according to the *PET* estimation method and the duration, *k*.

Severity of meteorological droughts (SMET)

Table 7 shows the estimates related to the number obtained from each type of SMET, for each of the three durations (*k*) and each weather stations processed. In general, the duration of three months showed the greatest dispersions in the SMET number, which in theory must be equal to half the number of years of records (*NA*), a value which is indicated for each weather station. The percentages quoted in Table 7 were calculated with the number of SMET found; therefore they add up to 100%.

The Thornthwaite method resulted in the percentages of each type of SMET, which are more dissimilar than those obtained with the reference *PET*. This happened in the three weather stations, but was more pronounced in Río Verde.

It can be stated that the percentages of each SMET that define the Turc and Hargreaves–Samani methods were quite similar to those obtained with the Penman–Monteith formula. This confirms the results in Table 6.

The numerical values in Tables 6 and 7 allow us to conclude that there is no significant influence on the annual RDI_{st} values, nor on the percentages of each type of SMET that they define, when the Hargreaves–Samani method is applied to any of the three weather stations processed. The Thornthwaite method is applicable only in the warm-humid climate of the Xilitla weather station.

Conclusions

The results of the application of RDI_{st} to the three weather stations processed in the state of San Luis Potosí, belonging to different climates, indicate that there is no significant influence on the annual RDI_{st} values or on the percentages of each type of meteorological drought that they detect, when using the empirical methods of Hargreaves–Samani and Turc to estimate monthly potential evapotranspiration (*PET*), in comparison with the results of the Penman–Monteith formula, taken as a reference.

This allows the RDI_{st} to be established as a robust meteorological drought index, which is practically independent of the *PET* estimation method.

The numerical calculation of the *PET*, according to the Penman–Monteith formula and the Hargreaves–Samani method, is remarkably different in terms of complexity. Therefore, the result in Table 6 indicating that the *MSE* is the lowest in the three climates studied, given such empirical criterion, is extremely important for its practical significance.

Appendix 1: Penman-Monteith Formula

Theoretical and operational equations

H. L. Penman, in 1948, was the first to obtain an equation that combines the energy required to sustain evaporation and an empirical description of the diffusion mechanism by which energy is removed from the evaporation surface as water vapor (Shuttleworth, 1993). Penman's formula led to a new evaporation estimation criterion called the *Combination Method*. Several researchers modified the Penman formula to take into account the effects of the evolution of aerodynamic conditions on the growth of the crop, the former through resistance factors. The resistance of the surface (r_s) on the water vapor flow in the stomata of the leaves and on the soil surface is distinguished from the aerodynamic resistance (r_a) that occurs due to the friction of the air flow over the vegetable surface. Although the exchange processes in the vegetation layer are much more complex, the measurements and calculations of latent heat flow, *λET,* have shown a high correlation, at least for a uniform grass surface. With such modifications the theoretical Penman-Monteith formula was obtained (Allen *et al*., 1998):

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a \cdot c_p\,(e_s - e)/r_a}{\Delta + \gamma(1 + r_s/r_a)} \quad \text{(A.1)}$$

where *λET* is the speed of evapotranspiration in megajoule per m^2 per day ($MJ/m^2/d$), Δ is the slope at one point of the saturation vapor curve versus the temperature in kilopascal per °C (kPa/°C), *Rn* is the net solar radiation in $MJ/m^2/d$, *G* is the flow of heat from the ground in $MJ/m^2/d$, ρ_a is the average density of air at constant pressure in kg/m^3, c_p is specific heat of the air at constant pressure in MJ/kg/°C, (e_s – e) is the vapor pressure deficit of air in kPa, r_a is the aerodynamic resistance in s/m, γ is the psychrometric constant in kPa/°C, and r_s the surface resistance in s/m.

When considering a hypothetical vegetation surface that is 12 cm high, with a fixed surface resistance of 70 s/m, and an albedo of 0.23 in active growth that completely shades the ground and does not lack water, the following operational Penman–Monteith formula (Allen *et al*., 1998) is obtained:

$$ET_o = \frac{0.408 \cdot \Delta \cdot (Rn - G) + \gamma \cdot [900/(Tt + 273)] \cdot u_2 \cdot (e_s - e)}{\Delta + \gamma \cdot (1 + 0.34 \cdot u_2)} \quad \text{(A.2)}$$

where *ETo* is the reference evapotranspiration in millimeters per day (mm/d) and the two new terms are *Tt*, which is the average air temperature at 2 meters high in °C, and u_2, which is the average wind speed at 2 m high in m/s. The value r_s = 70 s/m corresponds to a moderately dry soil surface resulting from frequent irrigation, approximately weekly.

To get Equation A.2 from A.1, the depth of water in mm/d can be expressed in terms of energy received per unit area. This energy refers to the heat needed to evaporate the specified water depth, and is known as *latent heat of evaporation* (*λ*), which is a function of the water temperature (*Ta*) and is calculated with the following equation in MJ/kg (Allen *et al*., 1998):

$$\lambda = 2.501 - 0.002361 \cdot Ta \quad \text{(A.3)}$$

Since the value of *λ* does not change much with *Ta*, *Ta* = 20 °C is used, and then *λ* is approximately 2.45 MJ/kg, that is, 2.45 MJ are required to evaporate one kilogram of water or one liter. Then, a 1 mm depth of water is equivalent to 2.45 MJ/m^2, since 1 mm per m^2 is a cubic decimeter, that is, one liter. The first numerical coefficient in Equation A.2 converts the radiation, expressed in MJ/m^2/d, to evaporation, in mm/d, and is equivalent to the inverse value of *λ* (1/*λ* = 0.408).

Equation (A.2) can be applied at intervals of one day, ten days, one month or even the total duration of crop growth or one year. To obtain *ETo* in mm/h, the numerator in the rectangular parenthesis is changed to 37 and all the variables are per hour rather than per day. For verification of the results, in humid tropical regions with a moderate average temperature (*Tt*≈20 °C), *ETo* varies from 3 to 5 mm/d; and with a hot climate, (*Tt* >30°C) it ranges from 5 to 7 mm/d, these intervals increase by one unit in the arid zones (Allen *et al*., 1998). In Mexico, applications of Equation A.2 have already been done by González–Camacho, Cervantes-Osornio, Ojeda-Bustamante and López-Cruz (2008), and Chávez-Ramírez *et al.* (2013).

Estimation of parameters Δ and γ

All the expressions presented below are from Allen *et al*. (1998) and are used to estimate the potential evapotranspiration (PET_j^i) in month *j* of each year *i*, which is required for the application of Equation 1. The slope (Δ in kPa/°C) in the vapor pressure curve of saturation at a point relative to the average air temperature (*Tt*) in °C, is calculated with the expression:

$$\Delta_j^i = \frac{4\,089 \cdot \left[0.6108 \cdot exp\left(\frac{17.27 \cdot Tt_j^i}{Tt_j^i + 237.3}\right)\right]}{\left(Tt_j^i + 237.3\right)^2} \text{ (A.4)}$$

The psychrometric constant (γ in kPa/°C) is determined with the following expression:

$$\gamma_j^i = \frac{c_p \cdot P}{\varepsilon \cdot \lambda_j^i} = \frac{1.62862 \cdot 10^{-3} \cdot P}{\lambda_j^i} \text{ (A.5)}$$

where $c_p = 1.013 \cdot 10^{-3}$ MJ/kg/°C and ε = 0.622 are the quotients of the molecular weight of water vapor to that of air, λ is estimated with Equation A.3 for the value of Tt_j^i in °C, and *P* is the atmospheric pressure at the site in kPa. This is estimated with the equation:

$$P = 101.3 \cdot \left(\frac{293 - 0.0065 \cdot z}{293}\right)^{5.26} \text{ (A.6)}$$

in which, *z* is the altitude in meters above sea level.

Estimation of radiations *Rn* and *G*

The net radiation (*Rn*) is equivalent to the difference between the net short-wave incident solar radiation (*Rns*) and the net long–wave solar radiation that is emitted or released (*Rnl*), that is:

$Rn = Rns - Rnl$ (A.7)

The *Rns* is the difference between the incident radiation solar (*Rs*) and the reflected one, so it is estimated with the expression:

$Rnsj = (1 - \alpha) \cdot Rsj$ (A.8)

where *α* is the albedo or coefficient of reflection of the vegetation cover, which is dimensionless. A value of 0.23 is adopted for the hypothetical reference grass. Rs_j must be expressed in MJ/m^2/d, therefore, the average monthly values, in cal/cm^2/d, from the maps proposed by Almanza and López (1975), or by Hernández *et al*. (1991), must be multiplied by 0.041868 to obtain MJ/m^2/d.

The long–wave energy emission rate is proportional to the absolute temperature of the surface raised to the fourth power. This relationship is known as the Stefan–Boltzmann's Law. Since water vapor, clouds, carbon dioxide, and dust absorb and emit long-wave radiation, their balance or net flow that leaves the earth's surface is estimated by correcting the Stefan–Boltzmann law for relative humidity and cloudiness, according to the following equation:

$Rnl_j^i = \sigma\left(Tt_j^i\right)^4 \cdot \left(0.34 - 0.14\sqrt{e_j^i}\right) \cdot \left[1.35 \cdot \left(\frac{Rs_j}{Rso_j}\right) - 0.35\right]$ (A.9)

where, $\sigma = 4.903 \cdot 10^{-9}$ MJ/K^4/m^2/d is Stefan–Boltzmann's constant, Tt_j^i is the average temperature of the month, in degrees Kelvin, equal to the degrees centigrade (°C) plus 273.16, e_j^i is the current partial vapor pressure in kPa and *Rso* is the solar radiation on clear days or without cloudiness, in MJ/m^2/d. This is estimated with the expression:

$Rso = (0.75 + 2 \cdot 10 - 5 \cdot z) \cdot Rej$ (A.10)

where, *z* is the altitude of the site and Re_j is the what is known as extraterrestrial radiation, in MJ/m^2/d. The quotient *Rs/Rso* must be less than one. The estimates of e_j^i, Re_j, and of the two missing terms in Equation A.2 (e_s and u_2) are detailed in the following Appendix.

By considering that the heat flow from the ground (*G*) is less than *Rn*, a very simple expression is used for its estimation, which considers the ground temperature to be similar to that of air; this is:

$G = c_s \frac{Tt_j + Tt_{j-1}}{\Delta d} \Delta z$ (A.11)

where, c_s = 2.10 MJ/m^3/°C is the caloric capacity of the ground, Δd is the interval in days, and Δz is the soil depth affected, which for lapses of one month or more is considered equal to 2 meters. Based on these numerical values, Equation A.11 for the first month, subsequent, and last month are:

$G_{j=1} = 0.14 \cdot (Tt_{j+1} - Tt_j)$ (A.12)

$G_j = 0.07 \cdot (Tt_{j+1} - Tt_{j-1})$ (A.13)

$G_{j=12NA} = 0.14 \cdot (Tt_j - Tt_{j-1})$ (A.14)

In equation A.14, *NA* is the number of years in the climatic record processed.

Appendix 2: Complementary climatic estimations

Extraterrestrial radiation

Re_j is the solar radiation at the top of the atmosphere in cal/cm^2/d. It is tabulated monthly and is a function of the latitude of the site (φ), in degrees. To avoid interpolation of Re_j, 12 third-degree Newton polynomials were developed. Their formula is applicable at latitudes from 10 to 40 degrees north (Campos–Aranda, 2005a):

$Re_j = b_0 + b_1(\varphi - 10) + b_2(\varphi - 10)(\varphi - 20) + b_3(\varphi - 10)(\varphi - 20)(\varphi - 30)$ (A.15)

Los b_i coefficients are as follows:

Months	b_0	b_1	b_2	b_3	Mes	b_0	b_1	b_2	b_3

Jan	760	−12	−0.075	1/600	Jul	880	5	−0.100	−1/1200
Feb	820	−9	−0.100	1/1200	Aug	890	2	−0.125	−1/1200
Mar	875	−5	−0.125	1/1200	Sept	880	−2.5	−0.150	1/1200
Apr	895	0	−0.125	−1/1200	Oct	840	−8	−0.075	−1/1200
May	890	4	−0.100	−1/400	Nov	780	−11.5	−0.025	−1/300
Jun	875	6	−0.100	−1/600	Dec	740	−12.5	−0.075	1/1200

The values of Re_j estimated with Equation A.15 must be multiplied by 0.041868 to obtain them in MJ/m^2/d.

Partial vapor pressure

To estimate e_j^i with Equation A.9, we remember that hotter air may contain more water vapor, whose maximum is the partial pressure of saturation vapor (e_s), in kilopascal (kPa), which is a function of temperature and is estimated with the following expression:

$$e_{sj}^i = 0.6108 \cdot exp\left[\frac{17.27 \cdot Tt_j^i}{(Tt_j^i + 237.3)}\right] \text{ (A.16)}$$

When there is less amount of water vapor than the maximum, the partial pressure of water vapor is designated by e, and then the relative humidity (HR) in percentage is:

$$HR = \frac{e}{e_s} 100 \text{ (A.17)}$$

If the air that contains any amount of water vapor equal to e is cooling, it reaches a point where e becomes e_s, and that temperature is called the *dew point* (t_*), which is estimated with Equation A.16. Solving for this gives us:

$$t*_j^i = \frac{237.3 \cdot \left[In\left(e_j^i/0.6108\right)\right]}{17.27 - \left[In\left(e_j^i/0.6108\right)\right]} \text{ (A.18)}$$

Having found that t_* is very close to the average monthly minimum temperature (t_j^i), a simple way of estimating the value of e_j^i is established. This was verified almost three decades ago by Arteaga-Ramírez (1989), and more recently by Cervantes-Osornio, Arteaga-Ramírez, Vázquez-Peña, Ojeda-Bustamante and Quevedo-Nolasco (2013).

Table A.1 shows the monthly average relative humidity data (Equation A.17), partial vapor pressure (*e*), and minimum temperature (*t*) for five meteorological observatories (SARH, 1982), which are surrounding the three weather stations that will be processed. Based on Equation A.18, using 6.108 instead of 0.6108, since *e* is in mbar, the corresponding dew point temperatures (t_*) were obtained. Then, the differences between *t* and t_* were calculated for their inspection and to determine the corrections to the value *t*, since theoretically these differences should be close to zero.

Table A.1. Monthly average values for several climatic elements in the five meteorological observatories indicated. *Average annual precipitation.

Description:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
Meteorological observatory: Saltillo (Coah.). *PMA** = 269.4 mm.													
Relative humidity (%)	62	59	54	54	58	62	65	68	72	70	64	62	62
Vapor pressure (mbar)	9.1	9.6	9.0	13.0	15.6	17.9	17.6	17.5	16.6	13.9	11.5	9.1	13.3
Dew point (t_* °C)	5.6	6.4	5.4	10.9	13.6	15.8	15.5	15.4	14.6	11.9	9.0	5.6	11.2
Minimum temp. (*t* °C)	5.2	6.8	8.7	12.7	14.7	16.4	16.5	16.2	14.5	11.6	8.0	6.3	11.4
Differences $t - t_*$ (°C)	–0.4	0.4	3.3	1.8	1.1	0.6	1.0	0.8	–0.1	–0.3	–1.0	0.7	0.2
Meteorological observatory: San Luis Potosí (SLP). *PMA* = 315.4 mm.													
Relative humidity (%)	51	43	39	37	47	56	60	61	65	63	57	56	52
Vapor pressure (mbar)	7.5	6.8	7.3	7.9	11.3	13.4	13.8	13.3	13.8	12.0	9.6	8.3	10.4
Dew point (t_* °C)	2.9	1.5	2.5	3.6	8.8	11.3	11.8	11.2	11.8	9.7	6.4	4.3	7.5
Minimum temp. (*t* °C)	6.2	7.4	9.9	11.9	13.4	14.2	13.5	13.5	13.2	10.7	8.1	6.5	10.7
Differences $t - t_*$ (°C)	3.3	5.9	7.4	8.3	4.6	2.9	1.7	2.3	1.4	1.0	1.7	2.2	3.2

Meteorological observatory: Río Verde (SLP). *PMA* = 484.9 mm.													
Relative humidity (%)	73	70	64	64	66	69	73	72	77	76	76	75	71
Vapor pressure (mbar)	12.8	13.6	14.8	17.2	19.7	21.3	20.9	21.4	20.9	18.4	15.6	13.7	17.5
Dew point (t_* °C)	10.6	11.5	12.8	15.1	17.3	18.5	18.2	18.6	18.2	16.2	13.6	11.6	15.4
Minimum temp. (t °C)	9.2	10.8	12.9	16.0	17.9	19.0	18.2	18.3	17.3	15.0	12.2	9.6	14.7
Differences $t - t_*$ (°C)	−1.4	−0.7	0.1	0.9	0.6	0.5	0.0	−0.3	−0.9	−1.2	−1.4	−2.0	−0.7
Meteorological observatory: Aguascalientes (Ags.). *PMA* = 537.2 mm.													
Relative humidity (%)	57	52	46	43	46	59	65	67	69	64	59	61	57
Vapor pressure (mbar)	8.8	8.9	9.4	10.1	12.2	14.8	15.3	15.6	15.2	13.0	10.5	9.6	11.9
Dew point (t_* °C)	5.1	5.3	6.1	7.1	9.9	12.8	13.3	13.6	13.2	10.9	7.7	6.4	9.5
Minimum temp. (t °C)	4.6	6.1	8.2	11.0	13.4	14.8	14.1	13.9	13.3	10.6	7.2	5.5	10.2
Differences $t - t_*$ (°C)	−0.5	0.8	2.1	3.9	3.5	2.0	0.8	0.3	0.1	−0.3	−0.5	−0.9	0.7
Meteorological observatory: Tampico (Tam.). *PMA* = 985.9 mm.													
Relative humidity (%)	81	81	80	82	81	82	80	80	81	79	79	80	80
Vapor pressure (mbar)	17.7	19.3	21.1	25.5	28.5	30.5	30.3	30.4	29.7	25.9	21.5	18.9	24.9
Dew point (t_* °C)	15.6	16.9	18.4	21.4	23.2	24.4	24.3	24.3	23.9	21.7	18.7	16.6	21.0
Minimum temp. (t °C)	14.1	15.7	17.6	20.8	22.9	23.9	23.8	24.1	23.1	21.2	18.3	15.7	20.1
Differences $t - t_*$ (°C)	−1.5	−1.2	−0.8	−0.6	−0.3	−0.5	−0.5	−0.2	−0.8	−0.5	−0.4	−0.9	−0.9

The corrections in °C suggested in Saltillo are combined for the Villa de Arriaga station (September to February with zero and March to August with −1.00) and for Aguascalientes (July to February zero and March to June −2.00), proposing: September to February with zero and March to August with −1.50. Data from the San Luis Potosí observatory were not used since they are not considered to be fully reliable. For the observatory of Río Verde, the recommended corrections are: March to August zero and September to February +1.20. Finally, in the Xilitla station, the correction suggested for the Tampico observatory, which is to add 0.60°C in all months, will be applied.

Average wind speed

Finally, regarding the estimation of the average wind speed (*v*) to be used in Equation A.2, the FAO has established four values according to the type of winds that occur in the region: (1) weak from 0.50 to 1.0 m/s, (2) moderate from 1 to 3 m/s, (3) severe from 3 to 5 m/s and (4) strong ≥ 5 m/s. It also points out that the average speed at 2 m high in more than 2 000 meteorological stations in the world is 2 m/s.

Campos-Aranda (2005b) processed average monthly wind speed data (m/s) from 31 meteorological observatories that had this data, with the number of records ranging from 8 to 20 years. He found that the mode of 2.05 m/s verifies the observed global mean value and results in a sample and population median of the order of 2.3 m/s. This value is recommended for the monthly average.

Solar radiation with temperature data

When the Rs_j maps of Almanza and López (1975), or Hernández *et al*. (1991) are not available, or one does not want to use monthly average values, an estimate based on the monthly difference between the maximum (T) and minimum temperature (t) of the air can be made, since such difference is related to the degree of cloudiness at the site. In general, on clear days or days without cloudiness, high temperatures are generated during the day and low at night, due to the fact that long–wave radiation is not absorbed or returned. The opposite occurs on cloudy days. The empirical operational equation is (Allen *et al*., 1998):

$$Rs_j^i = ka \cdot Re_j \sqrt{T_j^i - t_j^i} \quad \text{(A.19)}$$

in which, Rs_j^i is solar radiation, in MJ/m^2/d, *ka* is an adjustment factor that ranges from 0.16 to 0.19, with units 1/°C, and Re_j is extraterrestrial radiation in MJ/m^2/d. The value *ka* = 0.16 is used for inland locations, where air masses are not influenced by the sea, and *ka* = 0.19 is used in coastal areas where there is such an affectation. Allen *et al*. (1998) also indicate how Rs_j^i data from a nearby meteorological station can be transported to the location under study.

Appendix 3: Empirical estimation criteria for *PET*

Thornthwaite Method

This estimates the potential evapotranspiration (PET_j^i) of month *j* of year *i* based solely on the average temperature (Tt_j^i) in °C and the latitude of the site (LAT) in degrees. Its equation is (Mather, 1977; Campos–Aranda, 2005a, Xu, Singh, Chen, & Chen, 2008):

$$ETP_j^i = 16 \cdot \left(\frac{10 \cdot Tt_j^i}{IC_i}\right)^{\alpha} \cdot Fc_j \quad \text{(A.20)}$$

in which, IC_i is an annual heat index, equal to the sum of the 12 monthly indices, which are:

$$ic_j = \left(\frac{Tt_j^i}{5}\right)^{1.514} \quad \text{(A.21)}$$

The exponent *a* is a function of IC_i with the following empirical equation:

$$\alpha = 0.4924 + 1.792 \cdot 10^{-2} \cdot IC_i - 7.71 \cdot 10^{-5} \cdot IC_1^2 + 6.75 \cdot 10^{-7} \cdot IC_1^3 \quad \text{(A.22)}$$

Finally, Fc_j is a monthly average corrective factor function of the latitude of the site and the number of days of the month (*ndm*). This formula is:

$$Fc_j = \left(\frac{N}{12}\right) \cdot \left(\frac{ndm}{30}\right) \quad \text{(A.23)}$$

where *N* is the maximum sunlight or maximum number of hours with average monthly sunshine. For its estimation in the Mexican Republic, Campos–Aranda (2005a) proposed the following empirical expression:

$$N = A + B\,[\text{sen}\,(30\,nm + 83.5)] \quad \text{(A.24)}$$

in which, *nm* is the number of the month, with 1 for January and 12 for December; *A* and *B* are constants, a function of the latitude of the site (LAT) in degrees, with the following expressions:

$$A = 12.09086 + 0.00266 \cdot \text{LAT} \quad \text{(A.25)}$$

$$B = 0.2194 - 0.06988 \cdot \text{LAT} \quad \text{(A.26)}$$

Turc Method

In the early 1960s, L. Turc proposed the following equation to estimate the monthly and 10-day PET_j^i, which is a function of the average monthly temperature, Tt_j^i, of the incident solar radiation Rs_j, expressed in cal/cm^2/d, and of the average monthly relative humidity (Turc, 1961; Campos-Aranda, 2005a; Xu *et al*., 2008):

$$ETP_j^i = c_j \cdot \frac{Tt_j^i}{Tt_j^i + 15}\left(Rs_j + 50\right) \cdot FC_j^i \quad \text{(A.27)}$$

The coefficient c_j takes the following values: 0.40 for months of 30 or 31 days, 0.37 for February, and 0.13 for a period of 10 days. The corrective factor is applied when the average monthly relative humidity (HR_j^i) is less than 50%, its expression is:

$$FC_j^i = 1 + \left(\frac{50 - HR_j^i}{70}\right) \quad \text{(A.28)}$$

Hargreaves–Samani Method

Average daily potential evapotranspiration (ETP_j^i),in millimeters, were proposed in the early 1980s, exclusively based on the average temperature (Tt_j^i) expressed in degrees Fahrenheit and the daily average incident solar radiation (Rs_j^i) expressed in millimeters of evaporated water depth. Its equation is (Hargreaves and Samani, 1982, Campos–Aranda, 2005a, Xu et al., 2008):

$$ETP_j^i = 0.0075 \cdot Rs_j^i \cdot Tt_j^i \quad \text{(A.29)}$$

The incident solar radiation (Rs_j^i) can be estimated with the Angström formula (Jáuregui-Ostos, 1978, Allen *et al*., 1998) when there is insolation or actual sunlight (*n*) data, or with the monthly maps available for the Mexican Republic (Almanza and López, 1975; Hernández *et al*., 1991), which are reported in cal/cm^2/d. For the transformation of Rs_j into evaporated water depth per day, the following formula is used:

$$Rs_j^i = \frac{10 \cdot Rs_j}{Hv_j^i} \quad \text{(A.30)}$$

where Hv_j^i is the so–called latent heat of evaporation or energy needed in calories to evaporate 1 g or cm^3 of water. It is estimated with the following expression, with the average (Tt_j^i) monthly temperature in °C:

$$Hv_j^i = 595.9 - 0.55 \cdot Tt_j^i \quad \text{(A.31)}$$

The other empirical formula by Hargreaves-Samani can be consulted in Campos–Aranda (2005a), which is a function of extraterrestrial solar radiation and monthly average and minimum temperatures. An application of this criterion is given in Campos-Aranda (2014).

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