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Rainfall Distribution Functions for Irrigation Scheduling: Calculation Procedures Following Site of Olive (*Olea europaea* L.) Cultivation and Growing Periods

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Abstract

In Tunisia (36.5˚N, 10.2˚E, Alt. 10 m), rainfall is the major factor governing olive production. It is characterized by large variability in time and space, making yields of olive trees highly dependent on the amount of water received and timing. Thus, improvement of olive productivity by irrigation is necessary. This study aimed to determine the crop water needs of olive orchards and the rainfall frequencies at which they are covered following age and sites of olive production. For this purpose, the rainfall distribution functions are established for different cities of Tunisia (Tunis, Bizerte, Béja, Nabeul, Sidi Bouzid, Gabes and Sousse). For all sites and growing periods, the reference evapotranspiration (ET_0) was computed by using several formulas. Their performance against the Penman Monteith (PM) method was evaluated graphically and statistically in all considered cities in order to evaluate their accuracy for better adapting them to the existing environmental conditions, particularly when data are missing to compute ET_0-PM. Results presented herein show that the estimated ET_0 values strongly correlate with ET_0-PM at all sites and formulas with r values up to 0.88. Particularly, the methods of Turc and Ivanov appropriately predict the ET_0-PM in all climatic regions of Tunisia and may constitute an appropriate alternative for ET_0 estimation when data are missing to compute ET_0-PM. However, although the Turc method performs well with all climatic zones, arid and semi-arid, in western, northern and coastal areas of Tunisia, the Ivanov method appears to be more appropriate to the northern areas (Béja and Bizerte) characterized by semi arid climate and having annual rainfall of up to 450 mm, though a poorer agreement was found when using the Eagleman formula. Estimates of ET_0 by using the Hargreave-Samani (HS) formula for the east-southern area (Gabes) characterised by arid climate show satisfactory agreement with ET_0-PM estimates, corroborating previous findings reporting

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that the HS method performs well in most climatic regions, with the exception of humid areas where it tends to overestimate ET_0. It appears also that at a given site, the most appropriate method for ET_0 estimation at annual scale may be different from that giving the best value of ET_0 when considering the growing stages of the olive tree. The formula of Turc, although it was appropriate when estimating the annual ET_0 value for Sousse, it wasn't adequate at seasonal scale. Adversely, although the method of BC is suitable for stages 1, 2, 4 and 5 at Sousse, the appropriate method for the overall cycle is that of Turc. Results also show that the average annual value of ET_0-PM calculated by using full datasets from January to December is well correlated to the maximum and minimum daily estimates with r values ranging between 0.70 and 0.83. These variations indicate that there is no weather-based evapotranspiration equation that can be expected to predict evapotranspiration perfectly under every climatic situation due to simplification in formulation and errors in data measurement. Nevertheless we can say that when data are missing, ET_0 can be estimated with a specific formula, suggesting that of Turc for Tunis, Sidi Bouzid, Sousse and Béja at annual scale despite of their appartenance to different climatic regions, while the method of Ivanov is quite valuable for Bizerte and Nabeul. Determination of the crop evapotranspiration (*ETc*) on the basis of ET_0-PM computations following age and the growing periods show positive values of (*ETc*-P) at annual scale for Tunis, Nabeul, Sousse Bizerte and Beja when young olive plantations are considered, but for old trees, values are positive only for Tunis, Bizerte and Béja. Seasonal differences between *ETc* and P (rainfall) recorded during the irrigation period are negative even for young plantations. The lowest and highest deficits are observed at Béja and Gabes cities, respectively. The rainiest periods are December-February for Béja, Tunis and Bizerte and September-November for the other sites with similar trends for rainfall frequency (F). The driest period is that of July-August for all sites, with F values exceeding 0.9 in most cases. Only 10% of water needs are supplied by rainfall during this period of fruit development even for one year old orchards. Therefore, irrigation is needed all time for adult trees even at the rainiest locations. For young plantations, irrigation becomes necessary beginning from the second period of tree development, *i.e.* April-June for Bizerte, Béja, Nabeul and Tunis since the early spring period for both young and old plants for Gabes and Sidi-Bouzid. It appears from this analysis based on the seasonal rainfall frequencies and water needs computed with the PM-formula, that there is a need for irrigating olive plantations aging more than 5 years in most case studies and especially when olive is cultivated in the western areas of Tunisia. Irrigation is needed during the growing fruit period but also during the other seasons, when shoots grow. Results also indicate that the use of no adequate method to estimate ET_0 allowed overestimating or underestimating of water requirements. So it is desirable to have a method that estimates ET consistently well and future research is needed to reconcile which should be the standard method of calculating the change in the crop coefficient over time. However, despite a quite good performance of the PM-equation in most applications, particularly when it is used for irrigation scheduling purposes, some problems may appear because of lack of local information on values and determination of the effective rainfall. In conclusion we can say that on the basis of the results produced, we can decide for each region and growing period if complementary irrigation is needed or not. Indicative amounts are given for each case study. Also, it appears to our best knowledge that this work with that of Nasr (2002) [1] is the only one that has estimated ET_0 for the whole country using PM-ET_0 compared to other empirical methods, but we didn't test the possible advantages in using calibrated values for the radiation adjustment coefficient or temperature adjustment for dew point temperature estimation as proposed by Allen (1996) [2]. This calibration is therefore a line to be explored. Additional research is needed on developing crop coefficients that use the Penman-Monteith equation when calculating ET and a standardized method of calculating the time base for the crop coefficients preferably based on a growing degree day concept.

Keywords

Methods of ET_0 Computation, FAO-PM Method, Climatic Water Deficit, Irrigation Application, Rainfall Frequency

1. Crop Evapotranspiration and Methods of ET_0 Computation: Brief Review

Most water absorbed by roots is lost through leaf stomata. This process is driven by the climatic demand and involves the need of measuring many biological and environmental variables like evapotranspiration. A large number of formulas have been developed and/or improved from 1942 to 2005 to compute the monthly or the seasonal "consumptive water use" later termed reference evapotranspiration (ET_0), starting with the Blaney-Criddle formula (BC) method and ending with the Penman-Monteith equation (PM) [3]-[6].

Empirical methods were primarily based on solar radiation (Turc, 1961; Christiansen-Hargreaves, 1969; Hargreaves-Samani, 1985), temperature (Blaney-Criddle, original and modified, 1950) and relative humidity (Ivanov, 1954; Eagleman, 1967). The formulas of Penman (Penman Original, 1963) and FAO-PM [7] [8] are based on combination theory and necessitate intermediary calculi, involving simultaneous measurements of radiation, air temperature, humidity and wind speed. Calculation procedures are described in Rana and Katerji (2000) and Habaieb and Masmoudi-Charfi (2003) [6]-[9] and recently summarized by Sammis *et al.* (2011) [10].

Many of these formulas have been used for irrigation and water rights management and yield prediction, but some of them provided errors and large uncertainities because most evapotranspiration available data are site specific and are difficult to apply to other situations. For this reason a consultation of experts and researchers, with the *International Commission for Irrigation and Drainage* and the *World Meteorological Organization*, have been organized by the FAO in the 90th in order to review the methodologies and procedures adopted for determinating the crop water requirements (*ETc*). This consultation considered the PM-model as the most advanced method for *ETc* determination in commercial orchards. It is aimed to define the grass reference evapotranspiration, *i.e.*, the rate of evapotranspiration from an hypothetical crop approximately resembling the evapotranspiration from an extensive surface of a disease-free green well-watered grass cover of uniform height, actively growing, completely shading the ground, and with adequate water and nutrient supply. Though, it is selected as the method by which the evapotranspiration of this reference surface (ET_0) can be unambiguously determined, providing consistent ET0 values in all regions and climates. Indeed, as the methodology of ET_0-PM estimation was successfully applied at different time scales in various climatic regions of the world [11]-[24], it was adopted since the year 1998 as the referenced method [8].

As redefined by *The Food and Agricultural Organization of United Nations* [8], the PM-equation overcomes shortcomings of the previous FAO Penman method, providing values of ET_0 more consistent with actual crop water use data worldwide and was found to be more consistent over a wider range of climatic conditions than other equations [16]. It became the *American Society of Civil Engineers* (*ASCE*) *Standardized Reference ET equation* and the current recommended equation to calculate the evapotranspiration rate from non-water stressed crop, *i.e.*, the evaporation power of the atmosphere which is expressed by the reference crop evapotranspiration (ET_0).

The PM-equation has two components: the radiation component controls *ET* by providing energy to drive the ET process [20] and the wind and vapor pressure deficit component which "controls the rate of transport of water vapor from the plant and soil surface and the capacity of the air to absorb water vapor". But estimating all these parameters needs auxiliary sub-models locally calibrated or parameterizations for conductances [13]. This implies many uncertainties which are introduced through the parameterization of the other variables [25]. In addition, as most available evapotranspiration data are site specific and are difficult to apply to other situations, the panel of experts developed a simplified way to deal with evapotranspiration dependence on climate by relating it to standard reference evapotranspiration (ET_0) by the crop coefficient, K_c, which is defined as the ratio of the crop evapotranspiration to the reference evapotranspiration as: K_c = *crop ETc/grass ET*, where *ET* is the maximum daily, monthly or seasonal evapotranspiration determined under non-stressed conditions. It is an empirical seasonal factor relating the seasonal plant water usage for a specific crop to the total seasonal consumptive water use factor generated under experimental conditions. K_c depends on the development rate of the crop and varies following year, season, the amount of water available to roots and the effective transpiring leaf area which was used in the PM-model to estimate daily tree transpiration of whole trees [8] [12] [26]-[28]. But as optimal conditions are difficult to realize, crop coefficients were taken as the ratio of evapotranspiration of well-watered orchards.

However, although the PM-method is considered as the most rational and elaborated approach, it could not be used for reliable estimation of ET_0 with incomplete series of climatic data. The lack of full weather datasets in many parts of the world, particularly in remote areas, limits the application of ET_0-PM, which is a major problem. Indeed, computation of ET_0 with the PM-equation requires a large number of climatic data, which are often very scanty, forcing the user to choose some other alternatives. Alternative accurate approaches requiring limited data has led to a huge number of related studies focusing various climates [15]-[32]. These procedures have been tested by Nandagiri and Kovoor (2005) [33].

Basing upon former studies to compare the performance of ET temperature methods, mainly the study made by Jensen *et al.* (1990 and 1997) [27]-[34], when full weather data are lacking, ET_0 can be estimated either using the empirical Hargreaves-Samani (HS) equation [4], or empirically estimating R_n, VPD and U_2 for using in the ET_0-PM equation, including using data from neighbour weather stations [16]. Various ET temperature methods were then excluded, particularly the ET climatic equation of Thornthwaite (1948) [35], that largely underestimates ET_0 comparatively to ET_0-PM [36]. In both aforementioned methods the minimum set of data required consists of T_{max} and T_{min}. The latter approach for using the ET_0-PM with only T_{max} and T_{min} is called PM temperature (PMT) method and is also referred in literature as reduced set PM method [32]. Both the HS and PMT methods have received a continuous attention from research contrarily to the use of neighbour weather data. The recent methodology reported by Martí and Zarzo (2012) [37] based on principal component analysis to estimate ET_0 when no local climatic inputs are available may provide new developments in this domain.

The ET_0-PM is widely used to manage irrigation of orchards characterized by incomplete soil cover. Irrigation water supplies are computed on the basis of the crop evapotranspiration (*ETc*) and rainfall amounts (R). In Tunisia (36.5˚N, 10.2˚E, Alt. 10 m), rainfall is the main fresh water resource providing annually 36 Km^3 of water in average, of which only 3 km^3 could be potentially collected as runoff water in large dams [38]. Large spatio-temporal variability characterise rainfall distribution with annual amounts ranging between 1500 mm in the extreme north of the country (Mogods mountains) and less than 80 mm in the southern area (Sahara). Non-arid area is estimated only at 37,000 km^2 (24%), arid area at 55,000 km^2 (35%) and desert at 63,000 km^2 (41%) [39] [40]. Renewable groundwater resources are estimated at 1.7 km^3 and mostly used (83%) for agriculture [41]. About 500,000 ha of annual and perennial crops are irrigated permanently, amongst 66,000 ha of olives beneficiate regularly of complementary irrigation.

Olive (*Olea europaea* L.) is the main component of our agricultural system covering one third of the agricultural area which approximates 1400,000 ha. Most plantations are rainfed, receiving annually no more than 250 mm of rainfall. A major part of these falls is received during the autumn and winter (quiescent period) seasons and only 25% of this amount and perhaps less is profitable to the growing fruits (May to October), that's why fruit size and olive production remain highly dependent on water provided during that period and particularly in the centre and southern areas [42]-[44]. Yields fluctuate from year to year between 60,000 and 300,000 tons as well as the amount of extracted oil (16% to 26%). This situation is very uncomfortable for both orchadists and the government because olive benefits are the main financial resource for agriculture, and Tunisia has to provide obviously thousand tons of olive oil each year for exportation to the EU, which is a strategic partner.

Supplemental irrigation [40] of olive orchards has emerged during the last few decades as an appropriate practice that has the potential to improve their productivity and stabilize yields by reducing spatial and temporal production variability. It has been adopted in different parts of Tunisia, and even institutionalized as a major strategy to respond to growing water scarcity in the irrigated areas and at the same time to increase crop productivity in traditionally rainfed plantations. Furthermore, the Tunisian government has taken since the 90th through its financial and development programs to develop many water conservation strategies as building important hydraulic catchments [39]-[41]. Also, the government encourages farmers to densify the traditional plantations in order to increase their benefits and oil production and to plant olive trees at higher densities, by distributing in some cases free cuttings and N-fertilizers. All kind of waters, fresh, brakish [45] and even margines and waste waters [46] are used. With appropriate horticultural practices, olive production has risen significantly during this last decade, but crops still suffer from a large gap between applying the correct water needs and the optimal production because of summer water shortage and cyclic droughts [42]-[40] [47]-[49]. That's why, other methods and technologies like assisted drip irrigation [50]-[52], strategies of deficit irrigation [51] [53]-[55] and partial root irrigation [56] [57], fertigation, high yielding cultivars grown with high levels of input [58] [59], but also innovative techniques that ensure the best use of natural precipitation, should be promoted to improve the performance of the used practices. However, due to the limited available water resources, development of techniques and methods should target at the most profitable areas where the allocation of irrigation water could be optimized.

Consequently, as olive farming becomes more intensive, crops require greater economical inputs and the changes accompanying the new cultivation systems have revealed a lack of knowledge about management of these orchards. Many problems erase at field level particularly when irrigating them. A large number of orchardists practice irrigation during the high fruited years independently of tree age, LAI and soil coverage increases. Thus, the amount of water distributed to the orchard may not meet its seasonal water needs and sometimes, lead to a loss of large amounts of water, low water use efficiencies, low growth rates and even dratistic yields. Negative effects appear when water shortage occurs during the critical stages of flower differenciation (February) and fruit growth (June-September), but also during the period of flower induction, occurring during the previous summer. So, because fruits are produced on one year old shoots which elongates during the last year [60]-[62], water should be available during all these stages over two growing seasons to cover water needs with regard to the importance of each one of the physiological process involved during fruit development [63].

In many studies carried out in Tunisia [64]-[69] [52] [70] and elsewhere around the Mediterramean countries [14] [71]-[77], irrigation is applied as a compulsory practice when the tree is the most responsive to water. These works sought to evaluate the potential of using different irrigation amounts to complement rainfall. Results show that in environments characterized by alternating wet and dry seasons, adding small amounts of water during the growing season can increase water productivity many-fold. This potential of supplemental irrigation must be explored to make better use of the limited resources available. Other results show that olive production was almost unchanged when water supply increased up to 300 mm. This is well traduced by some quantitative relationships established between production and water supplies [47] [69] [57] and well described in the recent paper "*Manuel d'Irrigation de l'Olivier*, *Techniques et Applications*", published in Tunisia by Masmoudi-Charfi *et al.* (2012) [78].

Adequate irrigation management requires an accurate estimation of the whole orchard water losses [6] [13] [79]-[82]. This has been measured in olive plantations by using the water balance method [77] [80] [81] [83] and lysimeters [84] providing *in situ* measurements of the actual water used by plants cultivated under field conditions. This involves estimation of water used at specific time and location as well as the relationship between water consumption and biomass production [57] [69] [85] and its dependency with climatic data and soil coverage [69] [77]. But, when these values are applied at field level, some problems may arise inherent to the spatial representativeness of measurements. Necessarily, the field should be cultivated under the same conditions.

Nowadays, the general approach used to calculate the water requirements of olive orchards is the crop evapotranspiration ET [11] [13] [29] [68] [76] [77] [81] [86], a term more descriptive of the water sources involved, which are the amounts of water evaporated from the soil (E) and transpired by the plant (T) per unit area. These processes occur simultaneously and there is no easy way of distinguishing between them [8] [12] [13]. Plant evaporation measurements named transpiration (T) are difficult to perform and many parameters should be taken into account [11] [49] [83] [84] [87] [88]. Errors or/and consistent changes may arise [16] [25] following age, the anatomy of trees and their vigor, soil water availability and the evaporative demand. If water is not limiting factor, transpiration will be conditioned by leaf area. This may result in a problem of representativeness, since well developed olive trees, shading a large area may provide within the same orchard higher transpiration rates. Moreno *et al.*, (1996), Fernandez *et al.*, (2001) and Abid-Karray (2006) [14] [89] [90] measured this component by the heat pulse technique of Granier (1985) [91]. In Tunisia, Masmoudi-Charfi *et al.* (2013) [55], showed that tree transpiration of young olive trees cv., Chétoui, approximates 50% *ETc*. For soil evaporation, many alternative methods and models were proposed since the 70th [92]-[94]. However, although this component is theoretically well defined, it is difficult to measure for orchards and isolated trees. Most models used for this purpose are based on the fraction of solar radiation reaching the soil surface, which decreases over the growing period as the crop develops. Some attempts should be made to take into account the special inhomogeneity of the environment under the tree [81]. Works carried out in Centre Tunisia on ten years old trees of cultivars Picholine and Meski have shown that soil evaporation equals to 53% *ETc* [51]. In other studies made in Spain these components were measured under olive orchards with microlysimeters [94], while the approach developed by Villalobos *et al.* (2000) [12] is based on the PM-equation [8] [16] with the use of crop coefficients, taken equal to 0.3 - 0.4 for young trees and ranging between 0.5 and 0.7 for adult plants [95]. Specific values were recently determined in Tunisia for adult trees by Braham and Boussadia (2013) [96] for the period of flowering and fruit set.

This study was carried out in several geographical sites of Tunisia covering the most common regions of olive cultivation, which are characterized by different climates. The main objectives are: 1) to evaluate the potential and accuracy of different ET_0 calculation formulas for better adapting them to the existing environmental conditions;

2) to define for each location the most appropriate formula to determine ET_0 and 3) to determine the amount of irrigation application to olive orchards depending on seasonal rainfall amounts, tree age and the growing stages through the establishment of the rainfall distribution functions for each growing period and location. These objectives are set to support a wide range of irrigation management and water resources applications for use in regions where weather data are missing, incomplete or of questionable quality. For each site, the comparative study between ET_0-PM and the other estimates, allowed us to choose the formula that gives the most valuable values for a specific city using a limited number of climatic data.

2. Materials and Methods

2.1. Areas of Olive Cultivation and Sites of Study

In Tunisia olive trees are mostly present in the center and southern regions of the country, contributing with 72% in number and 88% in area (**Table 1**).

Olive is cultivated under different growing environments, systems (rainfed, irrigated) and densities (17 to 1250 trees/ha). Soil is generally clay-loamy in the north, where Mediterranean climate prevail, and salty in the centre and southern regions, characterized by hard and dry conditions with absolute temperature exceeding 40˚C during the summer months. Fresh water used for irrigation is available in the north and becomes scarcer and brackish elsewhere. Deep resources are found in the southern areas. Water is supplied to olive orchards during the dry season from May to October. Drip irrigation concerns less than 20% of plantations. Cities concerned with this study and their coordinates (Lat. 36˚ to 38˚, Long. 8˚ to 11˚, Alt. 2 m to 314 m) are shown in **Table 2** and **Figure 1**.

Table 1. Distribution of olive trees in Tunisia.

Area	% of total number	% of total area
North	28	12
Center	60	68
South	12	20
Total	57,000,000 trees	1,400,000 ha

Table 2. Coordinates of the studied cities.

Site	Localization	Main crops	%	agriculture	area	(%) Olive tree area
			Vegetables	Fruit trees	Cereals	
Nabeul	LAT: 36˚85'N LON: 11˚08'E, ALT: 30 m	Fruit trees, vine, vegetables	53.1	32.3		9.3
Sousse	LAT: 35˚76'N LON: 10˚75'E, ALT: 2 m	Fruit trees and vegetables	83.2			9.0
Sidi Bouzid	LAT: 34˚41'N LON: 8˚81'E, ALT: 314 m	Fruit trees, vine, wheat, vegetables		48.2	19.6	16.2
Gabes	LAT: 33˚88'N LON: 10˚10'E, ALT: 5 m	Fruit trees, vegetables	29.6	47.2		3.2
Tunis	LAT: 36˚83'N LON: 10˚23'E, ALT: 4 m	Fruit trees, vine, vegetables	48.9	35.3		10.4
Béjà	LAT: 36˚48'N LON: 8˚8'E, ALT: 144 m	Wheat/Annual crops/fruit trees		27.1	36.9	18.7
Bizerte	LAT: 37˚25'N LON: 09˚8'E, ALT: 3 m	Fruit trees, vine, annual crops	48.3	24.0		10.5
Tunisia		**Olive trees and Cereals**	**30.8**	**40.0**	**14.2**	**1,400,000 ha**

NB: fruit trees including olive trees. Remarks: 1. Although Sfax is the main region of olive cultivation it was not considered in the results because the climatic data are incomplete. 2. Climatic data used for the city of Sousse were recorded with an automatic climatic station located in Monastir, which is a locality of Sousse.

Figure 1. Cities of Tunisia.

Cities of Béja, Tunis, Bizerte and Nabeul are all situated in the North of the country, while Sousse and Sidi Bouzid are located in the Center, and Sfax and Gabes are both coastal sites of South Tunisia.

2.2. Metdology

2.2.1. Steps of Work

The following steps were followed in this study:

1) Computation of the monthly reference evapotranspiration (ET_0, mm) by using several formulas, comparing estimates to ET_0-PM computations;

2) Estimation of the crop evapotranspiration (*ETc*, mm) following age and the growing periods;

3) Establishment of the rainfall distribution functions for all growing periods and cites;

4) Visualizing *ETc* values on the rainfall distribution graphs;

5) Computing the climatic deficit (P-*ETc*) and determination of the irrigation water amounts (I, mm) following tree age and site.

On the basis of the results produced, we have to decide for each region and period of growth if complementary irrigation is needed or not. Indicative amounts are given for each case study.

2.2.2. Climatic Variables

Climatic data were provided by the *National Institute of Meteorology* (INM) website [92], covering many years (**Table 3**). Data used for this study are maximum and minimum temperatures (T_{max} and T_{min}, ˚C), maximum and minimum relative humidity (RH_{max} and RH_{min}, %), maximum (N, hours/day) and actual sunshine durations (n, hours/month), wind speed measured at 2 m height (U_2, m/s) and atmospheric radiation (R_a, Mj/m^2/day). The majority of the selected cities have the longest and nearly complete data records for the requested period.

Rainfall records are averages of 99 years-long-period (1901-2000). Values are presented in **Figure 2** following the regions and the growing periods of olive trees.

Annual rainfall amounts ranged approximately between 200 mm at Gabes, an east-southern area of Tunisia and 600 mm at Béja and Bizerte which are continental and coastal areas located in the western and northern areas of

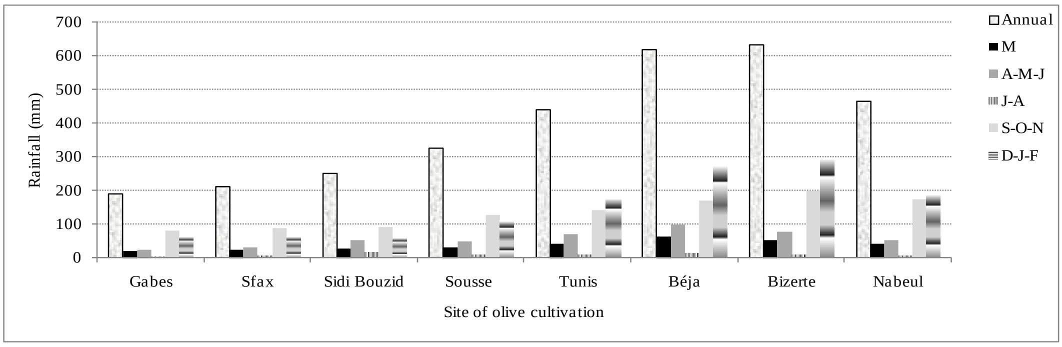

Figure 2. Rainfall amounts (P, mm) recorded in Tunisia following the growing period and sites of olive cultivation. Data are averages computed over 99 years-long-period between years 1901 and 2000.

Table 3. Climatic data recorded at the studied cities (INM, 2013) [97].

	Tunis	Nabeul	SB	Béja	Gabes	Bizerte	Monastir
T_{min} (˚C)	13.4	15.1	12.5	10.8	162	13.1	15.2
T_{max}˚C	23.5	22.7	25.3	239	243	22.6	24.0
U_2 (m/s)	4.2	3.0	2.8	42	34	3.9	4.5
es (mb)	2.3	2.4	2.5	23	26	2.2	2.5
R_a (Mj/m^2/day)	29.3	29.3	30.3	296	303	29.2	29.6
N (h/day)	5.0	12.0	12.0	120	12.0	12.0	12.0
HR (%)	68.9	72.4	59.0	650	63.0	70.8	66.0
n (h/month)	238.3	213.5	229.2	2048	265.0	242.2	223.5
Rainfall (P, mm/year)	449.7	468.1	251.8	628.3	190.1	634.6	328.1

the country, respectively (**Figure 1**). For Sousse and Sidi Bouzid, annual rainfall varied between 200 mm and 300 mm; all of them are located in the Centre of Tunisia. For Tunis and Nabeul, annual precipitations ranged between 400 mm and 500 mm. The driest month is July and the wettest is January.

Monthly average rainfall amounts (mm) recorded between 1901 and 2000 and their ecartypes are presented in **Figure 3** for the different cities. Largest variations between years were recorded during the rainiest months, *i.e.* December-February and September-November following the site. Lower variations between averge values were recorded during the summer months for all sites.

2.2.3. Climatic Characterization of the Studied Cities

The UNEP aridity index, which is adopted by the FAO and used worldwide, consists of the ratio of mean annual precipitation (P) to mean annual potential evapotranspiration ET_0 computed with the Thornthwaite method [35] [86] [98]. Values are presented in **Table 4** to climatically characterize the different cities on the basis of the following classification: *Hyper-arid*: 0 - 0.08, *Arid*: 0.08 - 0.2, *Semi-arid*: 0.2 - 0.5, *Dry sub-humid*: 0.5 - 0.65, *Moist sub humid*: 0.65 - 1, *Humid*: 1 - 2.

Values of aridity index obtained herein points to:

1) Tunisia is not concerned with humid and sub-humid climates.

2) Arid and semi-arid climate dominate the central and southern landscape.

3) Although Bizerte, a coastal region, has a relatively high annual precipitation accompanied with cold winters, it is not considered as a sub-humid region. Its AI is close to that of Béja, a continental area of north Tunisia.

4) Arid climate refers to the areas of west (Sidi Bouzid) and south (Gabes) Tunisia, although Gabes is a coastal site.

The Aridity Index AI ranges between 0.11 and 0.43, making Tunisia mostly concerned with the arid (Gabes and Sidi Bouid) and semi-arid climates (other cites). This agrees partially with Kassas (2005) [39], for which

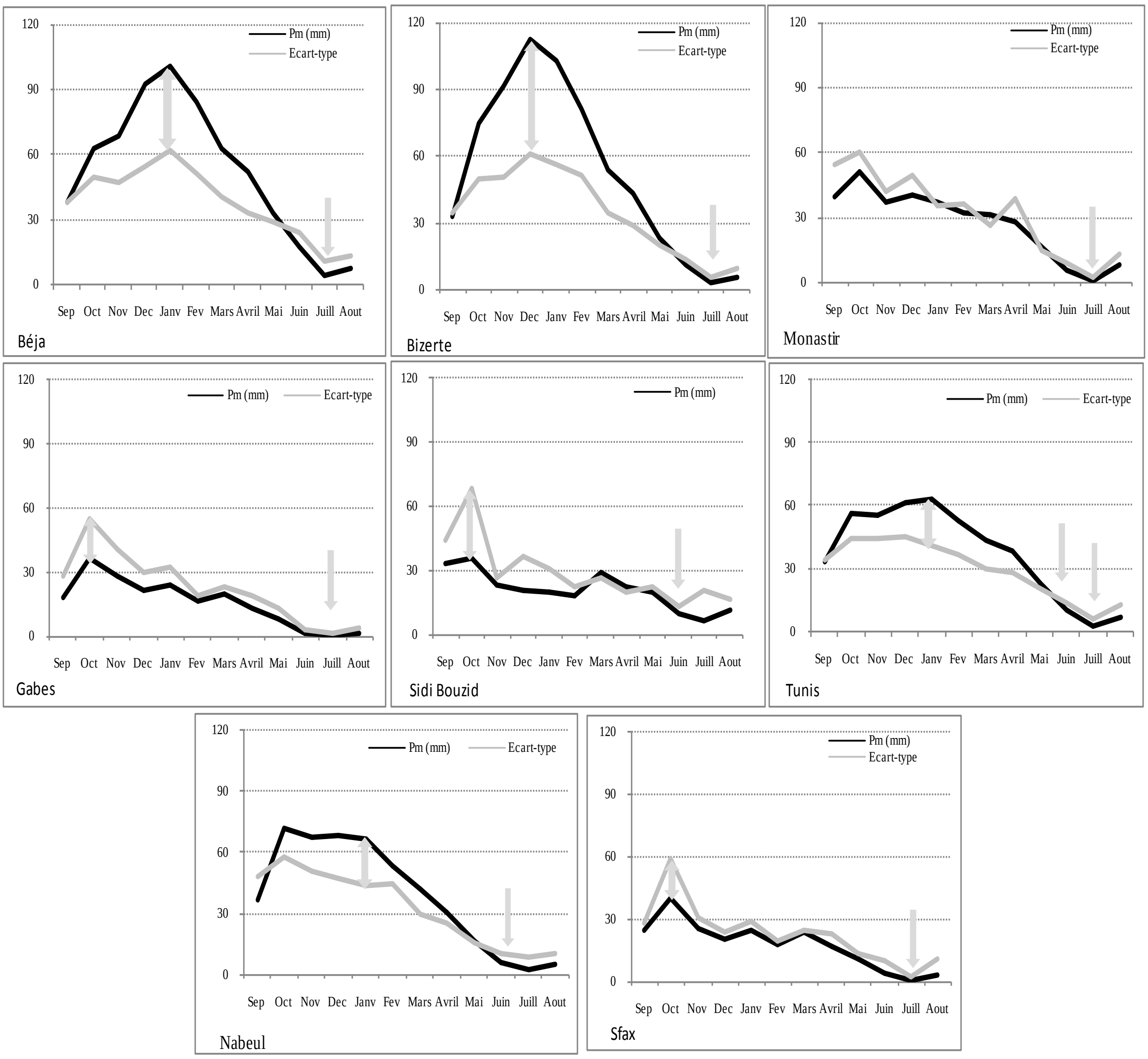

Figure 3. Monthly average rainfall amounts (mm) recorded between years 1901 and 2000 and the corresponding ecartypes.

Table 4. Mean annual values of Thornth waite (TW) potential evapotranspiration (mm), precipitation (P, mm) and index of aridity (IA) calculated for the studied cites.

	ET_0-TW (mm/year)	Rainfall (P, mm/year)	Index of aridity	Type of Climate
Tunis	1556.2	449.7	0.29	Semi-arid
Béja	1471.2	628.3	0.43	Semi-arid
Nabeul	1592.9	468.1	0.29	Semi-arid
Monastir	1679.5	328.1	0.20	Semi-arid
Gabes	**1762.0**	**190.1**	**0.11**	**Arid**
SB	**1634.9**	**251.8**	**0.15**	**Arid**
Bizerte	1494.4	634.6	0.42	Semi-arid

*Thornthwaite (TW) classification based on the UNEP aridity index [86]. SB: Sidi Bouzid city.

Tunisia is concerned with the semi-arid and arid climates in most areas and sub-humid in the extreme north of the country dominated by the mountains of *Kroumirie*, where the aridity index varies between 0.50 and 0.65.

The climate sub-regions of Tunisia produced herein based on the spatial variability of the aridity index, are in relatively good agreement with the results of "The precipitation based regionalization studies for Tunisia" illustrating the main structure of the Tunisian climate [41] but different from others produced by using other index to climatically characterise the different regions of the country. According to the FAO classification based on the length of the growing period, Tunisia is found out of the dry lands because crops can grow over a long period, exceeding 120 days (4 months).

2.2.4. Methods of ET_0 Calculation

Empirical formula used for ET_0 calculation is detailed in a previous paper published by Habaieb and Masmoudi-Charfi (2003) [9], and summarized in **Table 5**. The parameterization scheme for ET_0 (L ground $m^{-2} \cdot d^{-1}$) estimation is reported in **Table 6**. This schema adapted the PM-equation to be used with daily total net radiation (R_n, MJ ground $m^{-2} \cdot d^{-1}$) and the corresponding daily averages for air temperature (T_{mean}, ˚C), wind speed (U_2, $m \cdot s^{-1}$), vapor pressure deficit (VPD, kPa) and conductances [8] [13] [99]. The equation uses standard records of solar radiation (sunshine), air temperature, humidity and wind speed. Currently the climate data to calculate ET_0-PM are readily available from automated climate stations [1]. To ensure the integrity of computations, the weather measurements should be made at 2 m (or converted to that height, FAO 56) above an extensive surface of green grass, shading the ground and not short of water.

To appropriately compute the parameters of ET_0-PM (mm/day), the procedures proposed by Allen *et al.*, (1998) [8] should be followed as indicated above. Gavilán *et al.*, (2007) [20] reported that the methods proposed by Allen *et al.* (1998) [8] for estimating R_n and G are appropriate for ET_0 estimation for both daily and hourly

Table 5. Methods for ET_0 calculation and corresponding formulas. Parameters used in the formula are defined in the list of abbreviations below.

Method of ET_0 computation	Climatic variable	Formula
Blaney-Criddle modified (1950) by Doorenbos and Pruitt (1977)	$T_{average}$, n, N	$ET_o = (8 + 0.46\ T_{average}) \times n/N/i$
Hargreaves-Samani (1985)	$T_{average}$, R_a, T_{max}, T_{min}, R_a	Original: $ET_o = 0.0023\ R_a\ \Delta T^{0,5} \times (T_{average} + 17.8)$ Modified: $ET_o = 0.0035\ R_a\ \Delta T^{0,5} \times (T_{average} + 12.54)$
Christiansen-Hargreaves (1969)	R_s or R_a, U_2, $T_{average}$, $RH_{average}$, E	Original: $ET_o = 0.492\ R_s \text{ x } C_{TT} \times C_{WT} \text{ x } C_{HT}$ Modified: $ET_o = 0.324\ R_a \text{ x } C_{TT} \text{ x } C_{WT} \times C_{HT} \text{ x } C_{ST} \times C_R$
(1) Penman Original (1963) (2) Penman Monteith (1998)	$T_{average}$, e_o, U_2, n, N, R_a, $RH_{average}$,	$ET_o = [\Delta/(\Delta + \gamma) \times (R_n + G)] + [\gamma/(\Delta + \gamma) \times 15.36 \times (1 + 0,0062 \times U_2 \times (e^o - e))]$ $ET_o = \frac{[0.408 \times \Delta \times (R_n - G)] + [900 \times \gamma / (T + 273) \times (e^o - e) \times U_2]}{\Delta + [\gamma \times (1 + 0.34 \times U_2)]}$
Ivanov (1954)	T_{max}, T_{min}, T_m, e_o, $RH_{average}$, RH_{max}, RH_{min}	$ET_o = 0.0018 \text{ x } (T + 25)^2 \times (100 - e/e^o\ 100)$
Eagleman (1967)	T_{max}, T_{min}, $T_{average}$, e_o, $RH_{average}$, RH_{max}, RH_{min}	$ET_o = 0.035 \text{ x } e^o \times (100 - RH_{average})^{0.5}$
Stephens and Stewart (1965)	$T_{average}$, R_a, n, N	$ET_o = (0.014\ T_{average} - 0.37) \text{ x } R_s/1500/0.039$ with $R_s = (0.25 + 0.5\ n/N) \times R_a$
Turc (1961-1965).	$T_{average}$, $RH_{average}$, R_a, n, N	RH > 50%: $ET_o = 0.40\ (R_s + 50)\ T_{average}/(T_{average} + 15)$ RH < 50%: $ET_o = 0.40\ (R_s + 50)\ T_{average}/(T_{average} + 15)\ (1 + 50 - RH_{average})/70$ With $R_s = (0.25 + 0.5\ n/N) \times R_a$

where: $\mathbf{T_{max}}$: Maximum air temperature (˚C), $\mathbf{T_{min}}$: Minimum air temperature (˚C), $\mathbf{T_{average}}$: Mean daily air temperature (˚C), $\mathbf{T_{month}}$: Average monthly air temperature (˚C), **ΔT**: $T_{max} - T_{min}$ (˚C), Δ: Slope of the saturated vapor pressure curve (KPa ◦C^{-1}), *γ*: Psychrometric constant (KPa·˚C^{-1}), was set constant and equal to 0.066 (KPa/˚C), $\mathbf{U_2}$: Wind speed measured at 2 m height (m/s), $\mathbf{RH_{max}}$ **and** $\mathbf{RH_{min}}$: Maximum and minimum relative humidity of the air (%), $\mathbf{e_s}$: Saturated vapor pressure (KPa), $e_s = 0.5[e_o(T_{max}) + e_o(T_{min})]$, $\mathbf{e^o}$ $(_{Tmax})$: Saturation vapor pressure (KPa) at $T_{max,}$ $\mathbf{e^o}$ $(_{Tmin})$: Saturation vapor pressure (KPa) at $T_{min,}$ $\mathbf{e_a}$: Average value of vapor pressure or actual vapor pressure (kPa), $e_a = [e_{oTmax}\ RH_{min} + e_{oTmin}\ H_{max}]/200$. $e_o - e_a$: Saturated vapor pressure deficit of the air (KPa), VPD, $\mathbf{R_a}$ **and** $\mathbf{R_s}$: atmospheric and solar radiation (Mj/m^2/day). $\mathbf{R_{ns}}$: short radiations (Mj/m^2/day). $\mathbf{R_{nl}}$: long radiations (Mj/m^2/day). **N**: Maximum (Hours/day) sunshine duration, **n**: Actual sunshine duration (Hours/month), **n/N = p**: daylight hours monthly/annual daylight hours, **i**: number of days/month. $\mathbf{R_n}$: net radiation at the crop surface ($MJ \cdot m^{-2} \cdot day^{-1}$), R_n is computed as the algebraic sum of the net short and long short radiations. **K**: Constant of Boltzman. $\mathbf{ET_0}$: Reference evapotranspiration (mm/day). **G**: Soil heat flux density ($MJ \cdot m^{-2} \cdot day^{-1}$), flux of heat into the soil, set equal to zero to represent the condition of an isolated tree. $\mathbf{G_{month}}$: Monthly soil heat flux density ($MJ \cdot m^{-2}$), **PM**: Penman-Monteith equation.

Table 6. Daily ET_0 (mm) estimation procedure according to Penman-Monteith (PM) formula.

Variable	Unit	Formula	
T_{max}	˚C		
T_{min}	˚C	$T_{average} = (T_{max} + T_{min})/2$	˚C
$T_{average}$	˚C	Δ	
Altitude	m	γ	
U_2	m/s	$(1 + 0.34\ U_2)$	
	$\Delta/(\Delta + \gamma\ (1 + 0.34\ U_2))$		
	$\gamma/(\Delta + \gamma\ (1 + 0.34\ U_2))$		
	$(900/(T_{average} + 273)) \times U_2$		
Vapor Pressure Deficit (VPD)			
T_{max}	˚C	$e^o\ (T_{max})$	KPa
T_{min}	˚C	$e^o\ (T_{min})$	KPa
Saturation vapor pressure: $e_s = [e^o\ (T_{max}) + (e^o\ (T_{min})]/2$			KPa
e_a derived from air moisture			
RH_{max}	%	$e^{\circ}\ (T_{min}) \times RH_{max}/100$	KPa
RH_{min}	%	$e^{\circ}\ (T_{max}) \times RH_{min}/100$	KPa
	e_a: average value		KPa
Saturation vapour pressure deficit $(e_s - e_a)$ KPa			
Radiation			
Latitude			
Day		R_a	$MJ \cdot m^{-2} \cdot day^{-1}$
Month		N	Hour
n	Hour	n/N	
if R_s is not given: $R_s = (0.25 + 0.5\ n/N) \times R_a$			$MJ \cdot m^{-2} \cdot day^{-1}$
$R_{so} = [0.75 + 2\ (altitude)/100000] \times R_a$			$MJ \cdot m^{-2} \cdot day^{-1}$
	R_s/R_{so}		$MJ \cdot m^{-2} \cdot day^{-1}$
	$R_{ns} = 0.77\ R_s$		$MJ \cdot m^{-2} \cdot day^{-1}$
T_{max}	$MJ \cdot m^{-2} \cdot day^{-1}$	$\Delta\ T_{max}.\ K^4$	$MJ.m^{-2}.day^{-1}$
T_{min}	$MJ \cdot m^{-2} \cdot day^{-1}$	$\Delta\ T_{min}.\ K^4$	$MJ.m^{-2}.day^{-1}$
	$(\Delta\ T_{max},\ K^4 + \Delta\ T_{min}.\ K^4)/2$		$MJ \cdot m^{-2} \cdot day^{-1}$
e_a	KPa	$(0.34 – 0.14\ e_a^{1/2})$	
R_s/R_{so}		$(1.35\ R_s/R_{so} – 0.35)$	
$R_{nl} = (\Delta\ T_{max}.\ K^4 + \Delta\ T_{min}.\ K^4)/2 \times (0.34 – 0.14\ e_a^{1/2}) \times (1.35\ R_s/R_{so} – 0.35)$			$MJ \cdot m^{-2} \cdot day^{-1}$
	$R_n = R_{ns} – R_{nl}$		$MJ \cdot m^{-2} \cdot day^{-1}$
T_{mois}	$MJ \cdot m^{-2} \cdot day^{-1}$	G	$MJ \cdot m^{-2} \cdot day^{-1}$
T_{mois}^{-1}	$MJ \cdot m^{-2} \cdot day^{-1}$	$G_{month} = 0.14\ (T_{month} – T_{month} – 1)$	$MJ \cdot m^{-2} \cdot day^{-1}$
	$R_n – G$		$MJ \cdot m^{-2} \cdot day^{-1}$
	$0.408\ (R_n – G)$		$MJ \cdot m^{-2} \cdot day^{-1}$
Reference evapotranspiration			
$\Delta/(\Delta + \gamma)\ (1 + 0.34\ U_2) \times 0.408\ (R_n – G)$			mm/day
$[\gamma/(\Delta + \gamma)\ (1 + 0.34\ U_2)] \times (900/(T_{average} + 273)) \times U_2 \times (e_s\text{-}e_a)$			mm/day
$ET_0 = \frac{0.408\Delta(R_n - G) + [900\gamma/(T+273) \times U_2 \times (e_s - e_a)]}{\Delta + \gamma(1 + 0.34U_2)}$			mm/day

NB: Representative meanings of the variables indicated in **Table 6** are defined in the previous page.

time scales. Gong *et al.*, (2006) [17] performed a sensitivity analysis of ET_0-PM parameters and pointed to the very high influence of solar radiation and relative humidity in accurate estimation of ET_0. Recently, Allen *et al.*, (2011) [25] published a paper in which they present the factors governing measurement accuracy, while Popova *et al.*, (2006) [30] validate the FAO methodology for computing ET_0 with missing climatic data.

2.2.5. Growing Periods, Kc Values, Crop Water Needs and Irrigation Amounts

1) Growing periods

Olive is grown in the Mediterranean region over 270 days-long-period, beginning from March. Flower differenciation occurs from 15 February to 15 March while early fruit growth and pit hardening were observed from end of May to end of June. The ultimate fruit growth and oil synthesis were always observed beginning from 15 September. In order to adapt these stages to the available rainfall data, five growing periods were considered in this study, slightly different from the subdivisions made for the bisannual growing cycle [60] [63]:

1: March: shoot growth and flower development;
2: April-June: flowering and early fruit growth;
3: July and August: fruit development;
4: September-November: shoot growth, fruit enlargement, oil synthesis and olive maturation;
5: December-February: quiescence;

2) Crop coefficient (K_c) values

Values of K_c recommended by Allen *et al.*, (1998) [8] for adult olive trees ranged between 0.5 and 0.7. For young trees, Lebourdelles (1977) [65] recommended the use of values of 0.3 for trees aged 1 year and 2 years, 0.4 for trees of 3 - 5 years and 0.5 - 0.7 for adult plants. Recently, Braham and Boussadia (2013) [96] found for Tunisia values ranging between 0.46 and 0.51 (**Table 7**) which were determined by using the sap flow technique of Granier (1985) [91], with an average value of 0.48 in April and 0.47 for May.

3) Crop water needs and irrigation amounts

Crop water needs were determined following the FAO method where $ETc = ET_0 \times K_c \times K_r$. The coefficient K_r was introduced to take into account the soil coverage.

Irrigation water requirements were determined by subtracting the rainfall (P) that contributes to the evapotranspiration process from the estimated *ETc*.

3. Results

3.1. Spatial Pattern of ET_0-PM

The range of annual ET_0-PM varies from 1321.6 mm up to 1570.1 mm (**Table 8**), with maximum value observed in the arid area of Gabes (south-east of Tunisia) characterized by high temperature and radiation levels. Lowest annual ET_0 is recorded at Béja, a continental area of north-western Tunisia. Inversely, the highest seasonal ET_0-PM value is recorded in the continental area of Centre-western Tunisia (Sidi Bouzid), a mountainous area situated at 314 m height, while the lowest value is observed at Bizerte, a coastal and windy town of North Tunisia.

Daily maximum values ranged between 6.5 mm (Bizerte) and 7.1 mm (Sidi Bouzid), while minimums were

Table 7. Values of K_c obtained for olive trees cultivated in the Centre of Tunisia under adequate watering conditions [96].

Mois	Avril				Mai		
Stades phénologiques							
Kc	0,51	0,47	0,47	0,47	0,47	0,46	0,46

recorded in December and January and varied between 1.2 mm (Béja) and 2.2 mm (Sousse) (**Table 9**). Highest daily values of ET_0-PM are those recorded for the arid regions of Gabes and Sidi Bouzid, while the lowest are observed for the East (Bizerte) and West (Béja) northern areas.

The spatial pattern of ET_0 estimated using full datasets show a gradual increase of ET_0 to peak in July (**Figure 4**). Average annual value is well correlated to the maximum and minimum daily estimates, providing a poly

Table 8. Annual and seasonal ET_0-PM (mm).

Site	ET_0-PM (mm/year)	ET_0-PM (mm/season)
Tunis	1423.6	896.5
Nabeul	1484.7	871.1
SB	1485.0	907.1
Sousse	1527.1	879.8
Bizerte	1334.1	839.6
Gabes	1570.1	894.0
Béja	1321.6	885.7

Table 9. Average daily estimates of ET_0 (mm/day) computed with the PM-method.

PM (mm/day)	JAN	FEB	MAR	AVP	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC
Tunis	1.65	2.13	2.76	3.59	4.86	6.08	6.99	6.49	4.85	3.30	2.27	1.70
Sidi Bouzid	1.91	2.51	3.15	4.02	5.06	6.18	7.10	6.38	4.91	3.34	2.34	1.81
Sousse	2.18	2.72	3.35	4.02	4.87	5.75	6.64	6.24	5.23	4.01	2.94	2.16
Nabeul	2.05	2.65	3.25	3.96	4.62	5.90	6.63	6.19	5.12	3.54	2.72	2.10
Bizerte	1.60	1.98	2.60	3.38	4.38	5.65	6.54	6.17	4.67	3.10	2.05	1.62
Béja	1.19	1.78	2.32	3.28	4.59	5.93	7.01	6.56	4.83	2.94	1.72	1.16
Gabes	2.37	2.89	3.50	4.31	5.11	5.93	6.55	6.27	5.35	4.05	2.98	2.21
Max	2.37	2.89	3.50	4.31	5.11	6.18	7.10	6.56	5.35	4.05	2.98	2.21
Min	1.19	1.78	2.32	3.28	4.38	5.65	6.54	6.17	4.67	2.94	1.72	1.16

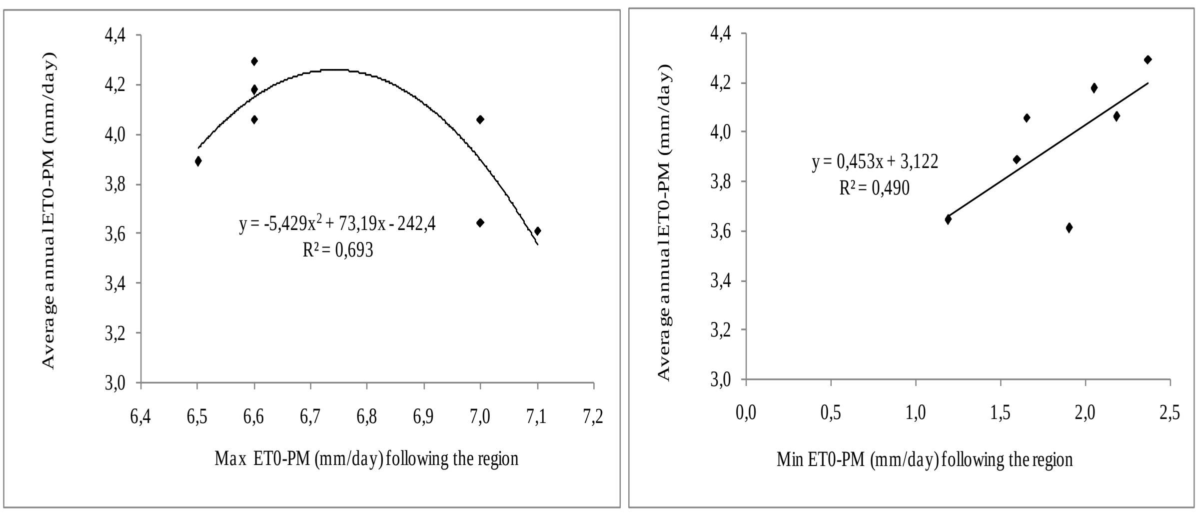

Figure 4. Statistic relationships between the average annual ET_0-PM (mm/day) and the maximum and minimum daily estimates computed for the studied cities ($p = 0.05$).

nomial curve in the first case (r = 0.83) and a linear positive correlation in the second case (r = 0.70). For regions where maximum ET_0-PM (July) exceeds 6.6 mm/day (Tunis = 7 mm; SB = 7.1 mm; Béja = 7.0 mm), minimum values recorded in winter are lower, ranging between 1.2 and 1.9 mm/day (Tunis = 1.7 mm; Sidi Bouzid = 1.9 mm; Béja = 1.2 mm). For the case of Sousse, Nabeul and Gabes, all coastal areas, maximum ET_0-PM is 6.6 mm (July) while minimum values reached 2.2 mm; 2.1 mm and 2.4 mm respectively. This is the result of the proximity of the sea which temperates the climate of the surrounding areas by decreasing the summer ET_0-PM values and increasing the winter ones.

Seasonal values computed following the growing periods show lower and higher estimates for west Tunisia (Beja) during winter-early spring and summer periods, respectively (**Figure 5**). ET_0-PM varies between 50 mm and 70 mm during period 5 (December-February) and reaches 100 mm (Gabes) in March (period 1). Estimates of ET_0 ranged between 100 mm and 180 mm during period 2 (April-June). Lower values recorded during period 1 and 2 are those of Béja and Bizerte. Maximums are recorded in July, exceeding 200 mm/month for all stations. Those recorded in August are slightly lower. During period 5 (September-November), ET_0-PM ranges between 50 mm and 150 mm.

The spatial distribution of ET_0 didn't follow the typical variability stipulating their increase southward and westward due to the decrease in latitude and the increase of altitude, respectively as reported by Razieia and Pereira (2013) [86]. However the spatial pattern of ET_0 computed at Bizerte resemble to that of Tunis, both located in North of Tunisia. Highest daily values were recorded for the arid regions of Gabes and Sidi Bouzid, while the lowest are observed for both the East (Bizerte) and West (Béja) northern areas. During summer months, Tunis and Béja present the highest values although they are situated at different latitudes and altitudes.

3.2. ET_0 Estimates Following the Empirical Formulas Compared to PM-Computations

The performance of empirical methods against the PM-ET_0 estimates in all considered sites are evaluated graphically (**Figure 6**) and statistically (**Table 11**). Significant positive correlations are observed with r values exceeding 0.88.

To assess the performance of these methods with respect to ET_0-PM, relative to all values for each station, the r values were determined. When the coefficient of correlation r is close to 1.0, most of the variation of the observed values can be explained by the linear model.

Variations between values are due to site characteristics and the formula used for ET_0 estimation. Values of r ranged between 0.880 and 0.999 (**Table 10**). The Eagleman method gave the highest values out of the range of those given by all the other formulas, while the lowest were provided by the HS formula. The lowest r coefficients were obtained for the cities of Sousse (r = 0.888) and Gabes (r = 0.885) when ET_0 is estimated by using the PO and Ivanov methods, respectively. These statistical coefficients are site specific even for the same species (e.g., olives) and the function for one orchard could not be used for the other.

Results show that when the series of climatic data is incomplete, ET_0 can be estimated by another empirical method depending on the available climatic variables. Formula that gives values of ET_0 approximating ET_0-PM—the universal reference estimating ET_0 method for each site are reported in **Table 7** and **Table 8**. Results show that methods of ST and SW are suitable for all stations. For Tunis, Nabeul and Sidi Bouzid, the method of Chr.

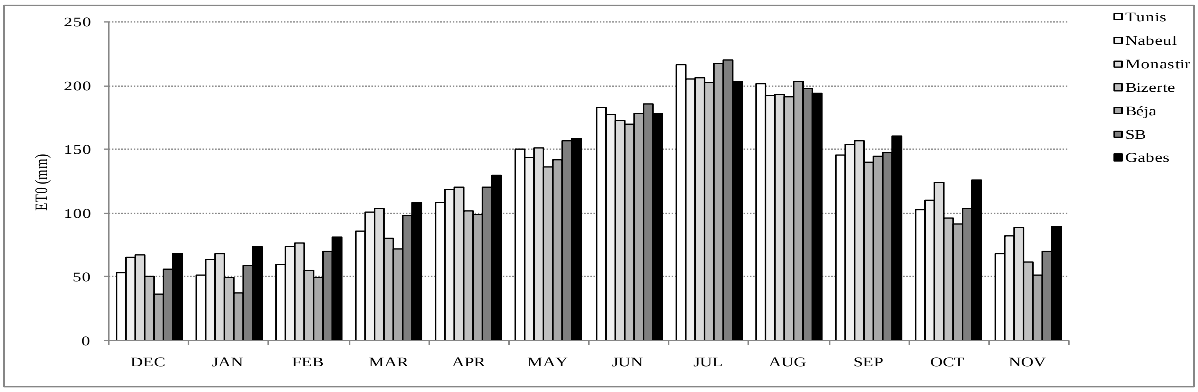

Figure 5. Values of ET_0 following the growing period and site of olive cultivation.

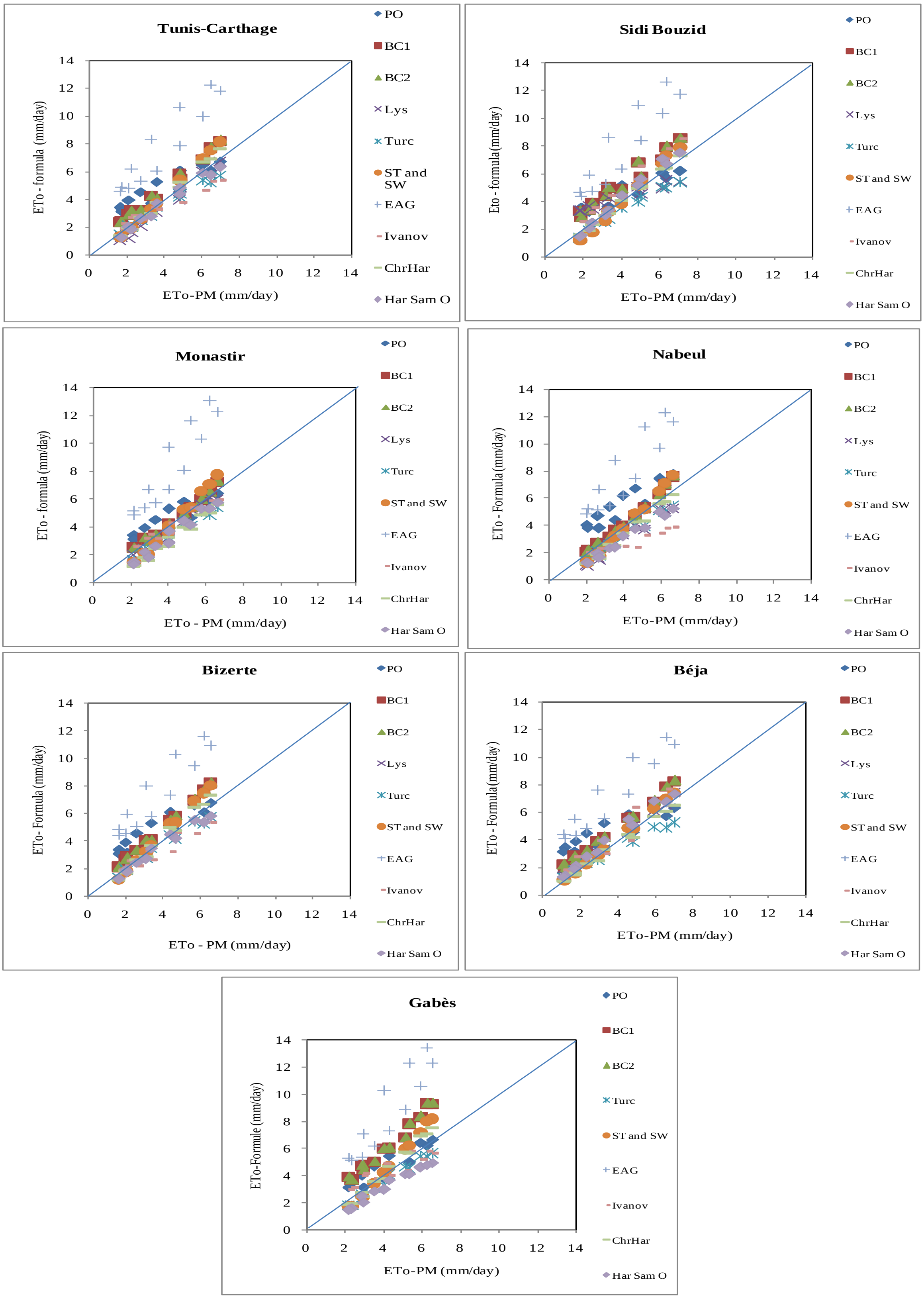

Figure 6. Relationship between ET_0-PM estimates and values of ET_0 determined by different calculation methods (mm/day) for all studied sites (p = 0.05).

Table 10. Coefficients of correlation obtained for the different sites. ET_0 estimated by several methods are compared to ET_0-PM computations.

	PO	BC1	BC2	Turc	ST and SW	EAG	Ivanov	Chr Harg	Harg Sam
Bizerte	0.918	0.999	0.999	0.988	0.999	0.935	0.961	0.996	0.988
Tunis	0.926	0.994	0.994	0.992	0.999	0.939	0.962	0.997	0.990
Béja	0.900	0.997	0.997	0.990	0.999	0.949	0.952	0.996	0.992
Gabes	0.926	0.991	0.991	0.979	0.995	0.909	0.885	0.991	0.970
Sousse	0.888	0.993	0.993	0.981	0.996	0.932	0.958	0.989	0.983
Nabeul	0.927	0.993	0.993	0.990	0.997	0.907	0.950	0.995	0.990
Sidi Bouzid	0.921	0.980	0.980	0.993	0.997	0.922	0.973	0.999	0.995

Harg. gave valuable results as well as that of BC for Bizerte, Béja, Gabes and Sousse, which are coastal regions.

However, the method of calculating the best ET_0 values changes following the growing period. The formula that gives values of ET_0 approximating ET_0-PM for each city (Table 11 and Table 12) indicates:

For Nabeul and Monastir, the BC formula is valuable for most periods of growth.

For Sidi Bouzid, the HS is valuable for stages 1, 4 and 5 and that of Chr. Harg. for stages 2 and 3 and the overall growing cycle.

For Bizerte, the method of ST and SW gives values of ET_0 approximating those of ET_0-PM for the overall growing cycle and stages 1 and 4.

The regions of Tunis, Sousse, Nabeul, Bizerte and Gabes are localized on the coast but a different 'response' is observed for a given stage of development.

For Bizerte, Tunis, Béja, Gabes, Sousse and Nabeul, the ST and SW method is noted as the best one for the overall cycle and for stages 4 for the first stations and 2 for Nabeul.

Linearly with ET_0-PM, the Ivanov method appropriately predicts ET_0 in all sites of Tunisia situated in the North and costal areas as it gives the lowest relative variation of ET_0. Table 12 suggests that the Ivanov method particularly performs well with the cities of Tunis, Nabeul and Bizerte characterized by semi arid climate, having annual rainfall of up to 450 mm. But when considering the lowest seasonal climatic deficit (P-*ETc*), it appears that the Turc formula is most appropriate for Tunis but also for Sousse, a coastal area of centre Tunisia. The Turc method also performs reasonably well in western areas, *i.e.* at Sidi Bouzid (arid climate) and Béja (semi-arid climate). Low climatic deficits were recorded at seasonal scale at both sites. For Gabes, the most appropriate method is that of Harg. Sam.

It appears from these results that the most appropriate method for ET_0 estimation at annual scale may be different from that providing the best value of ET_0 when considering the growing periods. Though, it is important to well define the researched objective. Indeed, the formula of Turc although it gave the best response for Sousse when estimating the annual ET_0 value, it wasn't the appropriate method when considering the growing periods. Adversely, although the method of BC is suitable for periods 1, 2, 4 and 5 at Sousse, the appropriate method for the overall cycle is that of Turc. This formula (Turc) is appropriate for Tunis, Sidi Bouzid, Sousse and Béja at annual scale despite of their appartenance to different climatic regions, while the method of Ivanov is quite valuable for Bizerte and Nabeul. At seasonal scale, the formula of BC is appropriate for stages 1, 4 and 5 for Tunis, Nabeul and Monsatir. That of Turc is valuable for stages 1 and 5 at Béja.

3.3. Crop Water Needs

Average *ETc* values are calculated for each site following age and the growing period (Table 13). The annual course of *ETc* computed by using ET_0-PM values shows minimum estimates close to 300 mm per year for young trees and maximum values ranging between 800 mm and 1000 mm for the older ones. Highest annual values of *ETc* are those recorded for Gabes, ranging between 335 mm and 894 mm depending on age. Minimum yearly values are those of Béja varying from 282 mm and 752 mm, due to ET_0 variations.

Water requirements (Table 13) increases during the first period of growth (March) from 15 mm to 40 mm for

Table 11. Appropriate methods for ET_0 calculation following the region and the growing period. Costal and northern cities.

	Tunis	Nabeul	Sousse	Bizerte
Rainfall amount (mm/year) and Ecartype	449.7/122.4	468.1/160.4	328.1/137.8	634.6/153.3
ET_0-PM (mm/year)	1424	1485	1527	1334
Frequency of water recovery following the stage of development	March: 40% April-June: 1% July-August: 0% Sept-Nov.: 33% Dec-Feb.: 91% Annual: 1%	March: 28% April-June: 0% July-August: 0% Sept-Nov.: 39% Dec-Feb.: 80% Annual: 14%	March: 17% April-June: 0% July-August: 0% Sept-Nov.: 24% Dec-Feb.: 36% Annual: 0%	March: 56% April-June: 0% July-August: 0% Sept-Nov.: 59% Dec-Feb.: 99% Annual: 19%
Lower relative variation of ET_0 in comparison with PM	Ivanov: +0.3% Turc: +12.4%	BC: −4.2% Ivanov: +28%	Ivanov: −1.8% Turc: +20.8%	Chr. Harg. = +1.6% Ivanov: +3%
Formula giving the lowest seasonal deficit	Ivanov Turc	Ivanov Harg Sam	Chr Harg = Turc	Ivanov Turc-Harg Sam
P-*ETc* > 0 for 1 - 2 years (annual)	All methods except EAG	All methods except PO and EAG	All methods except EAG	All methods
P-*ETc* > 0 for 3 - 5 years (annual)	All methods except EAG–PO-BC	Turc-Ivanov Chr Harg Harg Sam	Turc Chr Harg Harg Sam	All methods except EAG
P-*ETc* > 0 for 6 - 10 years (annual)	Turc Chr Harg	Ivanov	-	All methods except EAG, PO et BC
Adopted formula	**Turc**	**Ivanov**	**Turc**	**Ivanov**
r value correlation with PM	0.992	0.950	0.981	0.961
Best correlation with PM	ST and SW r = 0.999	ST and SW r = 0.997	ST and SW r = 0.996	ST and SW et BC r = 0.999
Adopted formula following the stage of development (low relative variability)	Stage 1: Chr Harg. Stage 2: Harg Sam O. Stage 3: PO Stage 4: ST and SW Stage 5: Turc	Stage 1: BC Stage 2: ST and SW Stage 3: Chr Harg Stage 4: BC Stage 5: BC	Stage 1: BC Stage 2: BC Stage 3: PO Stage 4: BC Stage 5: BC	Stage 1: ST and SW Stage 2: Harg Sam Stage 3: PO Stage 4: ST and SW Stage 5: Turc
Adopted formula	**Turc** HR > 50% $ET_o = \frac{0.40(R_s + 50)T_m}{(T_m + 15)}$ HR < 50% $ET_o = \frac{0.40(R_s + 50)T_m}{(T_m + 15)(1 + 50 - HR)/70}$ $R_s = (0,.25 + 0.5\ n/N) \times R_a$	**Ivanov** $ET_o = 0.0018 \times (T + 25)^2$ $\times (100 \times e/e^o\ 100)$	**Turc** HR > 50% $ET_o = \frac{0.40(R_s + 50)T_m}{(T_m + 15)}$ HR < 50% $ET_o = \frac{0.40(R_s + 50)T_m}{(T_m + 15)(1 + 50 - HR)/70}$ $R_s = (0.25 + 0.5\ n/N) \times R_a$	**Ivanov** $ET_o = 0.0018 \times (T_m + 25)^2$ $\times (100 - e/e^o\ 100)$
Variables involved	T_m, $RH_{average}$, R_a, n, N	T, e, e^o $e^o(T) = 0.6108 \exp (17.27 \times T)/(T + 237.3)$ $e = e^o \times RH_{average}/100$	T_m, $RH_{average}$, R_a, n, N	T, e, e^o

Table 12. Appropriate methods for ET_0 calculation following the region and the growing period. Continental and southern cities.

	Sidi Bouzid	Gabes	Béja
Rainfall amount (mm/year) and Ecartype	251.8/121.4	190.1/98.7	628.9/154.8
ET_0-PM (mm/year)	1485	1570	1322
Frequency of water recovery following the stage of development	March: 17% April-June: 0% July-August: 0% Sept-Nov: 8% Dec-Feb: 5% Annual: 7%	March: 5% April-June: 0% July-August: 0% Sept-Nov: 4% Dec-Feb: 14% Annual: 7%	March: 73% April-June: 4% July-August: 0% Sept-Nov: 48% Dec-Feb: 99% Annual: 18%
Lower relative variation of ET_0 in comparaison with PM	Harg Sam O.: +12.5% Turc: +20.4%	Chr Harg: −1.4% Harg. Sam: +23.9%	ST and SW: +2.4% Turc: +9.3%
Formula giving the lowest seasonal deficit	**Turc**	**Harg Sam** **Turc**	**Turc** **Chr Harg**
P-*ETc* > 0, 1 - 2 years (annual)	-	-	All formula
P-*ETc* > 0, 3 - 5 years (annual)	-	-	All formula except EAG
P-*ETc* > 0, 6 - 10 years (annual)	-	-	All formula except EAG, PO et BC
Adopted formula	**Turc**	**Harg Sam**	**Turc**
r value correlation with PM	0.993	0.970	0.990
Meilleure corrélation avec PM	Chr Harg r = 0.999	ST and SW r = 0.995	ST and SW r = 0.999
Adopted formula following the stage of development (low relative variability)	Stage 1: Harg Sam Stage 2: Chr Harg Stage 3: Chr Harg Stage 4: Harg Sam Stage 5: Harg Sam	Stage 1: Chr Harg Stage 2: Turc Stage 3: PO Stage 4: ST and SW Stage 5: Chr Harg	Stage 1: **Turc** Stage 2: Chr Harg Stage 3: Harg Sam Stage 4: ST and SW Stage 5: **Turc**
Adopted formula	**Turc** HR > 50% $ET_o = \frac{0.40(R_s + 50)T_m}{(T_m + 15)}$ HR < 50%: $ET_o = \frac{0.40(R_s + 50)T_m}{(T_m + 15)(1 + 50 - HR)/70}$ $R_s = (0.25 + 0.5\ n/N) \times R_a$	**Hargreaves-Samani** Original: $ET_o = 0.0023\ R_a\ \Delta T^{0,5}$ x $(T_m + 17.8)$ Modified: $ET_o = 0.0035\ R_a\ \Delta T^{0,5}$ x $(T_m + 12.54)$	**Turc** HR > 50% $ET_o = \frac{0.40(R_s + 50)T_m}{(T_m + 15)}$ HR < 50%: $ET_o = \frac{0.40(R_s + 50)T_m}{(T_m + 15)(1 + 50 - HR)/70}$ $R_s = (0.25 + 0.5\ n/N) \times R_a$
Variables involved	T_m, $RH_{average}$, R_a, n, N	T_m, R_a, T_{max}, T_{min}, R_a	T_m, $RH_{average}$, R_a, n, N

Béja following age, from 21 mm to 55 mm for Sidi Bouzid, from 18 mm to 48 mm for Tunis, from 21 mm to 46 mm for Nabeul, from 22 mm to 52 mm for Sousse, from 17 mm to 45 mm for Bizerte and from 23 mm and 61 mm for Gabes. For the other periods (April to November, 2 to 4), water needs increased consistently with values ranging between 87 mm and 254 mm for the coastal areas and from 90 mm to 266 mm for the continental locations. Minimum *ETc* values were recorded when the formulas of Turc, Chr. Harg, Harg.Sam and Ivanov are used.

Table 13. Water requirements of olive trees (*ETc*, mm) following age, site, growing periods and methods of ET_0 computation.

Bizerte	1	2	3	4	5	PM	PO	BC	Turc	STand SW	EAG	Ivanov	Chr-Harg	Harg-Sam O.
1 - 2 years	17	87	83	64	34	285	374	366	262	315	575	259	295	261
3 - 5 years	23	116	110	85	45	380	499	488	350	419	766	346	394	347
6 - 10 years	30	156	148	114	60	508	668	653	468	562	1026	463	527	465
>10 years	45	233	221	170	90	759	997	975	699	839	1532	691	787	695
Sousse	**1**	**2**	**3**	**4**	**5**	PM	PO	BC	Turc	STand SW	EAG	Ivanov	Chr-Harg	Harg-Sam O.
1 - 2 years	22	95	84	79	46	326	363	349	262	322	647	320	243	265
3 - 5 years	29	127	112	106	61	435	483	465	349	429	863	426	324	353
6 - 10 years	39	170	150	142	82	582	648	623	467	574	1155	571	434	473
>10 years	58	254	224	211	122	870	967	931	698	858	1725	852	649	707
Béja	**1**	**2**	**3**	**4**	**5**	PM	PO	BC	Turc	STand SW	EAG	Ivanov	Chr-Harg	Harg-Sam O.
1 - 2 years	15	90	88	62	27	282	360	362	239	285	556	315	260	312
3 - 5 years	20	120	118	82	36	376	481	483	319	380	741	420	347	416
6 - 10 years	27	160	158	110	48	504	644	647	428	509	992	562	464	558
>10 years	40	240	236	165	72	752	961	966	639	760	1482	839	693	833
Nabeul	**1**	**2**	**3**	**4**	**5**	PM	PO	BC	Turc	STand SW	EAG	Ivanov	Chr-Harg	Harg-Sam O.
1 - 2 years	21	94	83	74	44	317	378	497	291	366	678	353	353	258
3 - 5 years	28	126	111	99	59	423	505	662	389	488	904	471	470	344
6 - 10 years	38	168	149	132	79	566	676	887	521	654	1211	631	630	461
>10 years	56	251	223	198	118	846	1009	1325	777	977	1809	942	941	688
Tunis	**1**	**2**	**3**	**4**	**5**	PM	PO	BC	Turc	STand SW	EAG	Ivanov	Chr-Harg	Harg-Sam O.
1 - 2 years	18	95	88	68	36	304	370	371	263	320	602	279	307	277
3 - 5 years	24	126	117	90	48	405	494	495	351	426	803	373	410	369
6 - 10 years	32	169	157	121	64	543	661	663	470	571	1075	499	549	494
>10 years	48	252	234	181	95	810	987	989	701	852	1606	745	819	738
Sidi Bouzid	**1**	**2**	**3**	**4**	**5**	PM	PO	BC	Turc	STand SW	EAG	Ivanov	Chr-Harg	Harg-Sam O.
1 - 2 years	21	99	88	69	41	317	362	420	254	312	611	316	302	291
3 - 5 years	27	132	117	92	54	423	483	560	338	417	815	422	402	389
6 - 10 years	37	177	157	123	72	566	647	749	453	558	1092	565	539	520
>10 years	55	265	234	184	108	845	966	1119	676	833	1630	843	805	777
Gabes	**1**	**2**	**3**	**4**	**5**	PM	PO	BC	Turc	STand SW	EAG	Ivanov	Chr-Harg	Harg-Sam O.
1 - 2 years	23	100	83	81	49	335	378	497	291	366	678	353	353	258
3 - 5 years	30	133	111	107	65	447	505	662	389	488	904	471	470	344
6 - 10 years	41	178	149	144	87	599	676	887	521	654	1211	631	630	461
>10 years	61	266	223	215	130	894	1009	1325	777	977	1809	942	941	688

Maximum estimates are those obtained by the Eagleman formula.

Lysimetric values determined by Nasr (2002) [1] representing the effective need of water are significantly lower than *ETc* computed with the PM-formula (*ETc*-PM) for Tunis, Nabeul, Sousse and Gabes, which are coastal areas. Annual ratios between the lysimetric values and *ETc* ranged between 0.74 and 0.96 for these areas and approximate the unit for both Béja and Sidi Bouzid as shown in **Table 14**.

3.4. Water Deficit and Irrigation Amounts Following Location

Annual and seasonal values of (P-*ETc*) computed for all sites are reported in **Tables 15-21**. Negative values represent the amount of water needed by trees over the year or the irrigation period (May-September) to complement rainfall. Amounts of water available for the crop are designed by the sign (+). Details for all sites are decribed as follows:

Tunis: At annual scale all methods allow recovery of the crop water needs of trees aged one to five years except that of Eagleman. But this result is not suitable for such plantations at seasonal scale. Indeed, all values of (P-*ETc*) are negative even for the youngest orchards. The lowest difference between rainfall R and *ETc* is recorded with the Ivanov method (−72 mm). Thus the seasonal rainfall amounts are not suffisant to meet the crop water needs for all tranches of age. The method of Turc, recorded previously as the most appropriate for this region allow recovery of the crop water needs of olive plantations aged one to ten years at annual scale and provide low differences between R and *ETc* at seasonal scale. The amount of water needed at seasonal scale varies from 76 mm to 344 mm depending on age.

Nabeul: At annual scale all methods allow recovery of the crop water needs of trees aged one to two years except those of Eagleman and PO. All seasonal values of (P-*ETc*) are negative. The Ivanov method provides the lowest water deficit. Irrigation is needed for all kind of olive plantations from May to September. The amount of

Table 14. Ratio between the lysimetric values and *ETc* (mm) following the site and the growing period.

	M	A-J	Jt-A	S-N	D-F	Annual
	1	2	3	4	5	Cycle
Tunis	0.74	0.96	0.92	0.80	0.64	0.86
Nabeul	0.83	0.86	0.82	0.70	0.56	0.77
Sousse	0.83	0.90	0.93	0.93	0.77	0.89
Gabes	0.85	0.92	0.92	0.77	0.68	0.84

Table 15. Annual and Seasonal water deficits (P-*ETc*, mm) at the site of Tunis.

Annual water needs (mm)										
Method Age (Year)	PM	PO	BC	Turc	ST and SW	EAG	Ivanov	Chr Harg	Har Sam O.	Lysimeter
1 - 2	**+178.2**	**+111.8**	**+111.0**	**+219.0**	**+162.5**	−120.2	**+202.5**	**+174.7**	+205.1	**+220.6**
3 - 5	**+76.9**	−11.6	−12.7	**+131.3**	**+56.0**	−321.0	**+109.3**	**+72.3**	+112.8	**+133.5**
6 - 10	−60.5	−179.1	−180.6	**+12.4**	−88.5	−593.4	−17.1	**+66.8**	−12.5	**+15.3**
>10	−382.2	−505.2	−507.4	−219.3	−370.0	−1123.9	−263.3	−337.5	−256.4	**−215.0**
Seasonal water needs (mm)										
Method Age (Year)	PM	PO	BC	Turc	ST and SW	EAG	Ivanov	Chr Harg	Har Sam O.	Lysimeter
1 - 2	−105.6	−109.3	−138.9	−76.2	−131.4	−256.5	−71.9	−118.9	−91.0	−92.2
3 - 5	−169.1	−174.1	−213.6	−129.9	−203.5	−370.3	−124.2	−186.9	−149.7	−151.3
6 - 10	−255.3	−262.1	−314.9	−202.8	−301.3	−524.8	−195.2	−279.1	−229.3	−231.4
>10	−423.1	−433.3	−512.1	−344.8	−491.9	−825.7	−333.4	−458.7	−384.4	−387.5

Table 16. Annual and Seasonal water deficit (P-*ETc*, mm) at the site of Nabeul.

Annual water needs (mm)										
Method Age (Year)	PM	PO	BC	Turc	ST and SW	EAG	Ivanov	Chr Harg	Har Sam O.	Lysimeter
1 - 2	**+71**	−46	**+52**	**+136**	**+83**	−227	**+175**	**+123**	+150	**+145**
3 - 5	−35	−191	−60	**+52**	−19	−432	**+103**	**+35**	+70	**+64**
6 - 10	−178	−387	−211	−62	−157	−710	**+7**	−85	−37	**−46**
>10	−458	−770	−507	−285	−425	−1251	−181	−318	−247	**−260**
Seasonal water needs (mm)										
Method Age (Year)	PM	PO	BC	Turc	ST and SW	EAG	Ivanov	Chr Harg	Har Sam O.	Lysimeter
1 - 2	−115	−154	−133	−83	−133	−270	−40	−101	−77	−81
3 - 5	−177	−229	−201	−134	−201	−383	−77	−157	−126	−132
6 - 10	−261	−330	−292	−203	−293	−537	−127	−234	−192	−200
>10	−424	−528	−471	−337	−472	−836	−224	−385	−321	−334

Table 17. Annual and Seasonal water deficit (P-*ETc*, mm) at the site of Sidi Bouzid.

Annual water needs (mm)										
Method Age (Year)	PM	PO	BC	**Turc**	ST and SW	EAG	Ivanov	Chr Harg	Harg Sam O.	Lysimeter
1 - 2	−71	−116	−174	−8	−66	−365	−138	−63	−83	−87
3 - 5	−177	−237	−314	−92	−171	−569	−266	−166	−193	−198
6 - 10	−320	−401	−503	−207	−312	−846	−440	−306	−341	−348
>10	−599	−720	−873	−430	−587	−1384	−778	−579	−631	−641
Seasonal water needs (mm)										
Method Age (Year)	PM	PO	BC	Turc	ST and SW	EAG	Ivanov	Chr Harg	Har Sam O.	Lysimeter
1 - 2	−113	−103	−157	−74	−131	−272	−148	−116	−129	−86
3 - 5	−177	−164	−236	−125	−201	−389	−224	−181	−199	−141
6 - 10	−264	−247	−343	−195	−297	−548	−327	−269	−294	−216
>10	−434	−409	−552	−330	−483	−858	−527	−442	−478	−362

water needed at seasonal scale varies from 40 mm to 224 mm depending on age.

Sidi Bouzid: The deficit of water is recorded at both annual and seasonal scales. Rainfall amounts are not suffisant to cover the crop water needs even those of one and two years old plantations. Irrigation is thus needed for all kinds of olive orchards. The method giving the lowest value of (P-*ETc*) is that of Turc. The amount of water needed at seasonal scale varies from 74 mm to 330 mm depending on age.

Sousse: At annual scale all methods allow recovery of the crop water needs of trees aged one and two years except that of Eagleman. At seasonal scale, the deficit is present for all tranches of age with lowest differences recorded for both methods: Turc and Chr. Harg. Seasonal rainfall is not suffisant to cover the crop water needs and irrigation is needed from May to September with amounts ranging between 95 mm and 351 mm depending on age.

Gabès: Water deficit is present at seasonal and annual scale. The rainfall amounts are not high enough to meet the crop water needs even for young plantations. The most valuable method giving the lowest deficit is that of Harg. Sam. Irrigation is requested at seasonal scale with amounts ranging between 128 mm and 374 mm depending on tree age.

Table 18. Annual and Seasonal water deficit (P-*ETc*, mm) at the site of Soussse.

Annual water needs (mm)										
Method Age (Year)	PM	PO	BC	Turc	ST and SW	EAG	Ivanov	Chr Harg	Harg Sam O.	Lysimeter
1 - 2	**+50**	**+13**	**+27**	**+114**	**+54**	−271	**+56**	**+133**	**+111**	**+85**
3 - 5	−59	−107	−89	**+27**	−53	−487	−50	**+52**	**+23**	−12
6 - 10	−206	−272	−247	−91	−198	−779	−195	−58	−97	−144
>10	−494	−591	−555	−322	−482	−1349	−476	−273	−331	−401
Seasonal water needs (mm)										
Method Age (Year)	PM	PO	BC	Turc	ST and SW	EAG	Ivanov	Chr Harg	Harg Sam O.	Lysimeter
1 - 2	−130	−130	−140	−96	−151	−303	−114	−95	−105	−120
3 - 5	−192	−193	−205	−147	−220	−423	−170	−145	−159	−179
6 - 10	−277	−277	−294	−216	−314	−585	−247	−214	−232	−259
>10	−442	−442	−468	−351	−497	−902	−398	−347	−375	−415

Table 19. Annual and Seasonal water deficit (P-*ETc*, mm) at the site of Gabes.

Annual water needs (mm)										
Method Age (Year)	PM	PO	BC	Turc	ST and SW	EAG	Ivanov	Chr Harg	Har Sam O.	Lysimeter
1 - 2	**−134**	**−177**	**−296**	**−90**	**−165**	**−477**	**−152**	**−152**	−57	**−82**
3 - 5	**−246**	−304	**−461**	**−188**	**−287**	−703	**−270**	**−269**	−143	**−176**
6 - 10	−398	−475	−686	**−320**	**−453**	−1010	**−430**	**−429**	−260	**−304**
>10	−693	−808	−1124	−576	−776	−1608	−741	−740	−487	**−553**
Seasonal water needs (mm)										
Method Age (Year)	PM	PO	BC	Turc	ST and SW	EAG	Ivanov	Chr Harg	Har Sam O.	Lysimeter
1 - 2	−171	−178	−254	−148	−212	−355	−157	−196	−128	−151
3 - 5	−235	−244	−346	−204	−289	−480	−216	−267	−177	−208
6 - 10	−321	−333	−469	−279	−394	−649	−295	−364	−244	−285
>10	−488	−507	−710	−427	−598	−978	−450	−553	−374	−435

Bizerte: At annual scale all methods allow recovery of the crop water needs of trees aged one to five years except that of Eagleman. Other methods like that of Turc allow also recovery of water needs of older trees, to ten years old. Thus, irrigation is needed during the fruit growth season with amounts ranging between 72 mm and 323 mm depending on age, computed with the method of Ivanov wich provid the lowest deficits.

Béja: At annual scale all methods allow recovery of the crop water needs of trees aged one to five years except that of Eagleman. The most appropriate formula is that of Turc providing the lowest deficit. Irrigation should be applied during summer months from May to September with amounts of water ranging between 49 mm and 296 mm depending on tree age.

The method of Turc appears as the most appropriate for Tunis, Sousse, Sidi Bouzid and Béja while the method of Ivanov is adaquate for Bizerte and Nabeul. For Gabes the method of Harg Sam gave the most adequate values. The main climatic data requested are temperature, humidity and insolation, which are available in most stations. These formulas can be used specifically for these stations when the climatic data are not available to compute ET_0-PM, particularly the solar radiation.

Table 20. Annual and Seasonal water deficit (P-*ETc*, mm) at the site of Bizerte.

Method / Age (Year)	PM	PO	BC	Turc	ST and SW	EAG	Ivanov	Chr Harg	Har Sam O.	Lysimeter
Annual water needs (mm)										
1 - 2	**+360**	**+271**	**+279**	**+383**	**+330**	**+70**	**+386**	**+350**	**+384**	
3 - 5	**+256**	+146	**+157**	**+295**	**+226**	−121	**+299**	**+251**	**+298**	
6 - 10	+137	−23	−8	**+177**	**+83**	−381	**+182**	**+118**	**+180**	
>10	−114	−352	−330	−54	−194	−887	−46	−142	−50	
Seasonal water needs (mm)										
Method / Age (Year)	PM	PO	BC	Turc	ST and SW	EAG	Ivanov	Chr Harg	Har Sam O.	Lysimeter
1 - 2	−100	−119	−147	−84	−136	−245	−72	−119	−86	
3 - 5	−160	−185	−222	−139	−208	−352	−123	−184	−141	
6 - 10	−241	−274	−324	−212	−305	−498	−191	−273	−216	
>10	−398	−448	−523	−355	−494	−783	−323	−446	−361	

Table 21. Annual and Seasonal water deficit (P-*ETc*, mm) at the site of Béja.

Method / Age (Year)	PM	PO	BC	Turc	ST and SW	EAG	Ivanov	Chr Harg	Har Sam O.	Lysimeter
Annual water needs (mm)										
1 - 2	**+296**	**+218**	**+216**	**+339**	**+293**	**+22**	**+263**	**+318**	**+266**	**+288**
3 - 5	**+202**	+97	**+95**	**+259**	**+198**	−163	**+158**	**+231**	**+162**	**+192**
6 - 10	**+74**	−66	−69	**+150**	**+69**	−414	**+16**	**+114**	**+20**	**+61**
>10	−174	−383	−388	−61	−182	−904	−261	−115	**−255**	**−195**
Seasonal water needs (mm)										
Method / Age (Year)	PM	PO	BC	Turc	ST and SW	EAG	Ivanov	Chr Harg	Har Sam O.	Lysimeter
1 - 2	−88	−86	−124	−49	−97	−220	−101	−75	**−105**	−92
3 - 5	−151	−148	−199	−98	−162	−326	−168	−133	**−173**	−156
6 - 10	−236	−232	−300	−165	−251	−471	−258	−212	**−265**	−243
>10	−402	−395	−498	−296	−424	−753	−435	−367	**−445**	−413

Values of (*ETc*-P) computed for the irrigation season, from May to September, are negatives. The deficit of water is present even for young plantations. Rainfall amounts were insuffisant to meet the crop water needs of this species during the period of fruit growth. These amounts should be supplied by irrigation. The lowest deficit is observed at Béja and the highest at Gabes. At annual scale, values of (*ETc*-P) are positive for Tunis, Nabeul, Sousse, Bizerte and Beja when young olive plantations are considered. For older trees, values are positive only for the northern areas of Tunis, Bizerte and Béja. This last location is the only case where water needs are covered for olive trees aged 6 to 10 years. So there is a need for irrigating olive plantations aging more than 5 years and especially when olive is cultivated in the western areas. Irrigation is needed during the growing fruit period but also during the other seasons, when shoots grow.

3.5. Rainfall Distribution Functions and Recovery of Crop Water Needs

Rainfall distribution functions were established for each city following the growing periods (**Figure 7**).

Rainfall distribution functions present different evolutionary. For rainy regions like Béja, Nabeul and Bizerte,

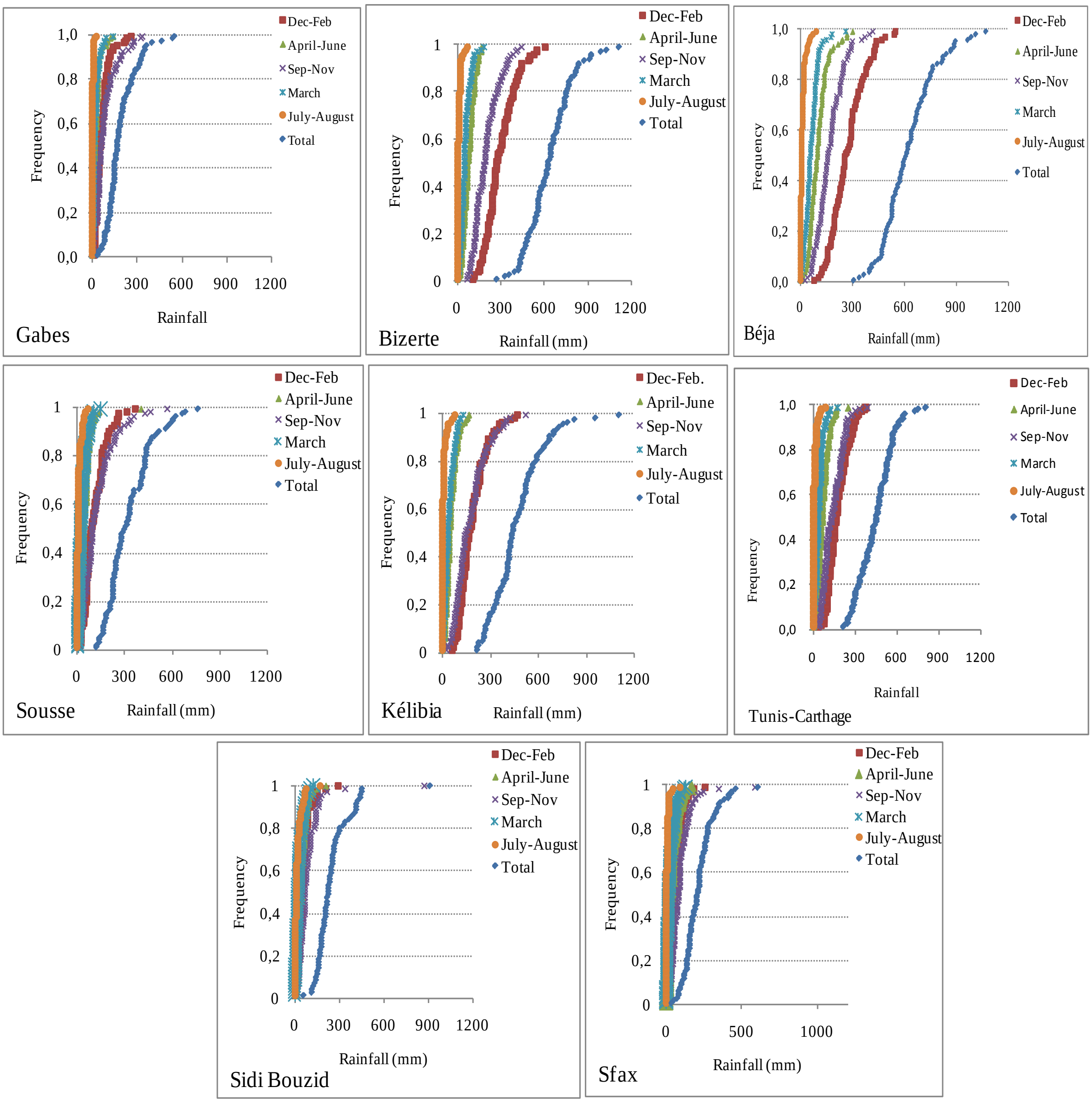

Figure7. Rainfall distribution functions following site of olive cultivation and the growing periods.

the curves looks separate, while those of Gabes and Sidi Bouzid are close one another. On the basis of these seasonal and annual distributions of rainfall, the frequencies of non-satisfactory were determined following tree age and location. Values are reported in **Table 22**. As shown in the following table, the frequencies of non-satisfactory (F) vary consistently from location to another and following the growing period. During July-August, F values exceed 0.9 in all cases and only 10% of water needs are supplied by rainfall even for the rainiest areas like Bizerte. For young trees aged one to five years, rainfall amounts meet excactly the crop water needs at Béja and Bizerte. Rainfall amounts cover 60% to 85% *ETc* of trees aged 6 to 10 years at Bizerte and Béja and trees aged one to five years at Nabeul and Tunis. About 50% *ETc* of one year old trees are covered by rainfall at Sousse. Less than 20% of water needs are covered at Bizerte and Béja for old trees aged more than 10 years, at Nabeul and Tunis for trees aged 6 to 10 years, at Sousse for trees aging 3 to 5 years and at Sidi Bouzid for of one year and two years old trees.

It appears from these results based on the seasonal rainfall frequencies and water needs computed with the PM formula that irrigation supply is necessary all time for trees aging more than 10 years even for the rainiest

Table 22. Frequencies of non-satisfactory of water needs following age and location.

Bizerte	1	F	2	F	3	F	4	F	5	F	T	F
1 - 2 years	17	0.101	87	0.611	83	0.917	64	0.009	34	0.008	285	0.011
3 - 5 years	23	0.148	116	0.828	110	0.999	85	0.050	45	0.005	380	0.038
6 - 10 years	30	0.216	156	0.945	148	0.999	114	0.150	60	0.004	508	0.216
>10 years	45	0.441	233	0.990	221	0.999	170	0.409	90	0.003	759	0.815
Sousse	**1**	**F**	**2**	**F**	**3**	**F**	**4**	**F**	**5**	F	**T**	**F**
1 - 2 years	22	0.440	95	0.905	84	0.999	79	0.353	46	0.15	326	0.541
3 - 5 years	29	0.590	127	0.958	112	0.999	106	0.541	61	0.29	435	0.818
6 - 10 years	39	0.740	170	0.999	150	0.999	142	0.673	82	0.471	582	0.924
>10 years	58	0.840	254	0.999	224	0.999	211	0.860	122	0.64	870	0.990
Béja	**1**	**F**	**2**	**F**	**3**	**F**	**4**	**F**	**5**	F	**T**	**F**
1 - 2 years	15	0.083	90	0.446	88	0.990	62	0.039	27	0.003	282	0.009
3 - 5 years	20	0.104	120	0.687	118	0.999	82	0.134	36	0.005	376	0.031
6 - 10 years	27	0.193	160	0.879	158	0.999	110	0.299	48	0.006	504	0.218
>10 years	40	0.268	240	0.960	236	0.999	165	0.521	72	0.009	752	0.822
Nabeul	**1**	**F**	**2**	**F**	**3**	**F**	**4**	**F**	**5**	F	**T**	**F**
1 - 2 years	21	0.282	94	0.884	83	0.990	74	0.117	44	0.000	317	0.175
3 - 5 years	28	0.376	126	0.886	111	0.999	99	0.248	59	0.009	423	0.427
6 - 10 years	38	0.547	168	0.990	149	0.999	132	0.411	79	0.048	566	0.782
>10 years	56	0.723	251	0.999	223	0.999	198	0.615	118	0.203	846	0.960
Tunis	**1**	**F**	**2**	**F**	**3**	**F**	**4**	**F**	**5**	F	**T**	**F**
1 - 2 years	18	0.163	95	0.761	88	0.945	68	0.150	36	0.011	304	0.171
3 - 5 years	24	0.284	126	0.850	117	0.999	90	0.275	48	0.015	405	0.370
6 - 10 years	32	0.398	169	0.980	157	0.999	121	0.456	64	0.021	543	0.768
>10 years	48	0.598	252	0.990	234	0.999	181	0.668	95	0.089	810	0.990
Sidi Bouzid	**1**	**F**	**2**	**F**	**3**	**F**	**4**	**F**	**5**	F	**T**	**F**
1 - 2 years	21	0.479	99	0.909	88	0.999	69	0.499	41	0.37	317	0.790
3 - 5 years	27	0.593	132	0.846	117	0.999	92	0.666	54	0.56	423	0.930
6 - 10 years	37	0.732	177	0.860	157	0.999	123	0.764	72	0.74	566	0.930
>10 years	55	0.832	265	0.999	234	0.999	184	0.984	108	0.953	845	0.934
Gabes	**1**	**F**	**2**	**F**	**3**	**F**	**4**	**F**	**5**	F	**T**	**F**
1 - 2 years	23	0.694	100	0.843	83	0.999	81	0.653	49	0.496	335	0.916
3 - 5 years	30	0.782	133	0.929	111	0.999	107	0.713	65	0.605	447	0.942
6 - 10 years	41	0.880	178	0.999	149	0.999	144	0.814	87	0.780	599	0.999
>10 years	61	0.952	266	0.999	223	0.999	215	0.826	130	0.860	894	0.999

NB: Period 1: March; Period 2: April-June; Period 3: July-August; Period 4: September-November and Period 5: December-February. Only the PM formula is adopted for *ETc* estimation.

locations as Bizerte and Béja where 20% only of the water needs are satisfied by rainfall. For younger plantations, irrigation becomes necessary beginning from the second period of development, *i.e.* April-June for Bizerte, Béja, Nabeul and Tunis. For the other stations, and particularly for Gabes and Sidi-Bouzid, irrigation is necessary for both young and old trees during the early spring period.

Figures 8-11 present the annual and seasonal distribution of rainfall expressed in terms of frequencies with

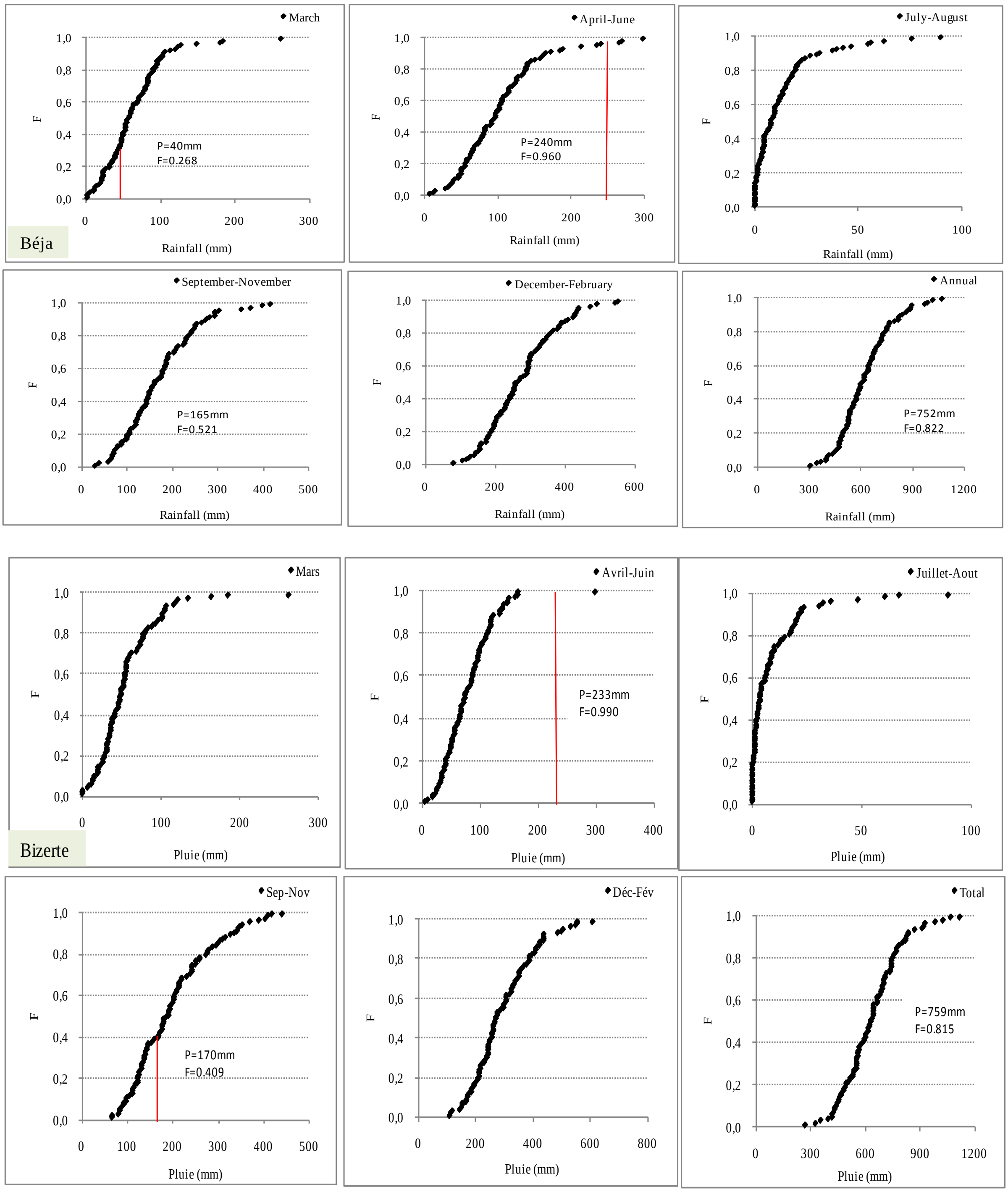

Figure 8. Rainfall distribution functions established for the sites of Béja and Bizerte with series of data recorded during 90 years-long-period and following the growing periods. Bars represent the amount of water needed (*ETc*, mm) for each period computed with the ET_0-PM formula for 10 years old trees.

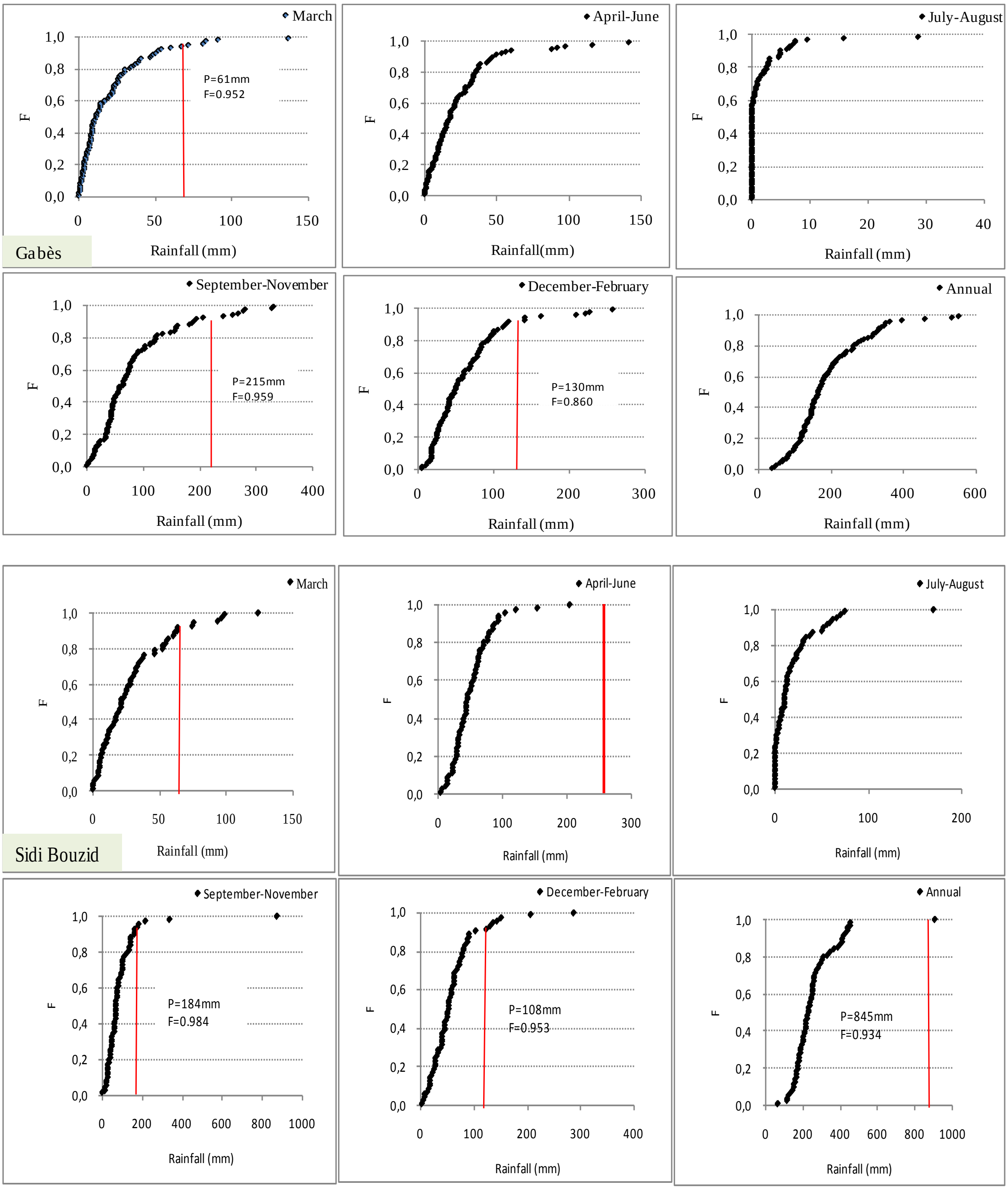

Figure 9. Rainfall distribution functions established for the sites of Gabes and Sidi Bouzid with series of data recorded during 90 years-long-period and following the growing periods. Bars represent the amount of water needed (*ETc*, mm) for each period computed with the ET_0-PM formula for 10 years old trees.

bars representing the amount of water needed for each period of growth following the site.

Rainfall distribution functions established for the first growing period (March), for period 4 (September-November) and period 5 (December-February) showed that an important fraction of water needs, ranging between 60% and 90% is covered by rainfall supplies at Bizerte and Béja. For Nabeul and Tunis, Water amounts needed during stages 1, 4 and 5 for plants aged one to 10 years are correctly covered by rainfall. A similar situation

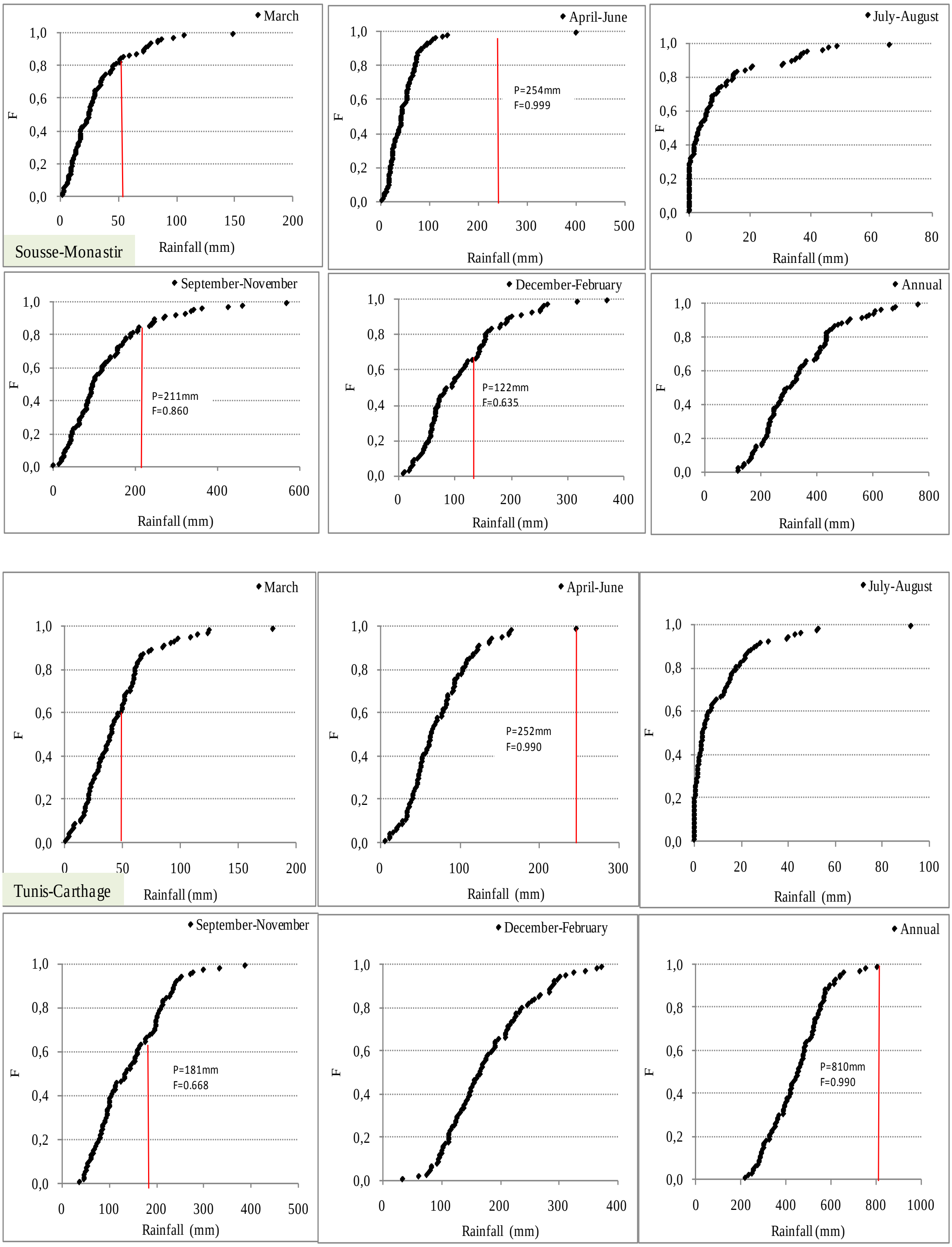

Figure 10. Rainfall distribution functions established for the sites of Sousse and Tunis with series of data recorded during 90 years-long-period and following the growing periods. Bars represent the amount of water needed (*ETc*, mm) for each period computed with the ET_0-PM formula for 10 years old trees.

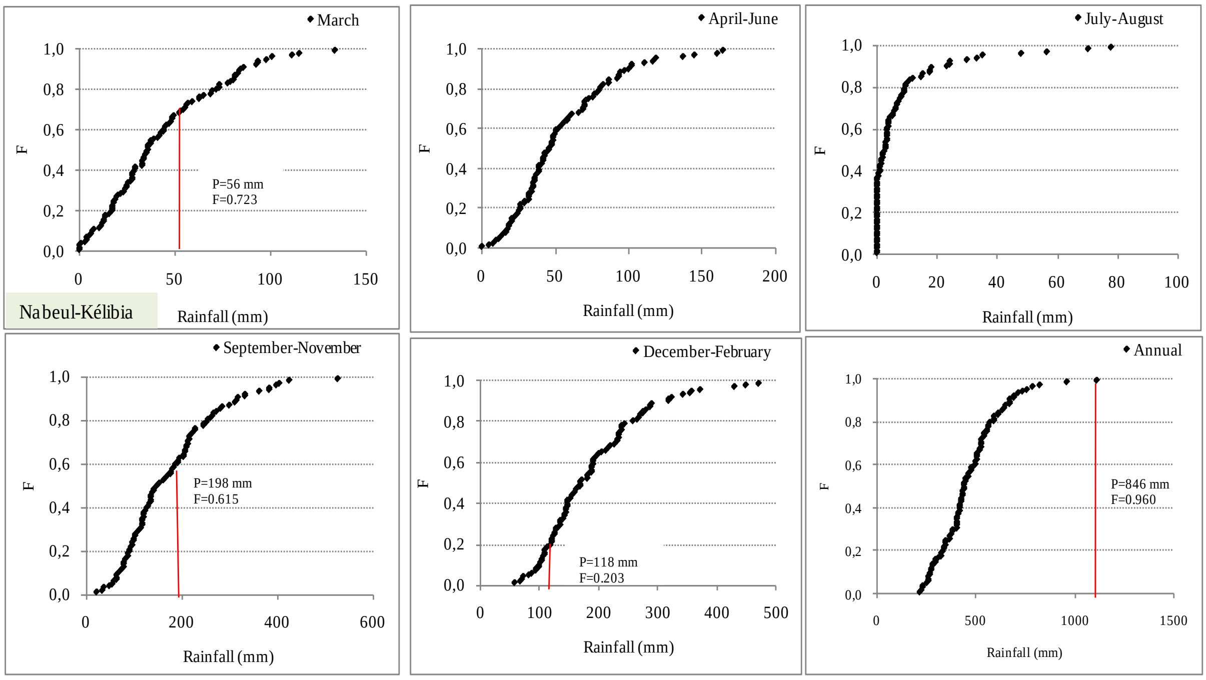

Figure 11. Rainfall distribution functions established for the site of Nabeul-Kélibia with series of data recorded during 90 years-long-period and following the growing periods. Bars represent the amount of water needed (*ETc*, mm) for each period computed with the ET_0-PM formula for 10 years old trees.

is observed for Sousse where plantations aged one to five years are correctly supplied by rainfall received during stages 1, 4 and 5. For the other locations, less than 50% of water needs are covered by rainfall from September to March.

For the period of April-June, *i.e.*, the period of flowering and early fruit development (period 2), rainfall amounts meet the crop water needs of young trees partially with a fraction ranging between 10% and 55% (40% at Bizerte, 10% at Monastir, 55% at Béja, 15% at Nabeul, 24% at Tunis, 10% at Sidi Bouzid and 16% at Gabes). For adult plants amounts of rainfall are insufficient to cover their water requirements. Therefore irrigation is needed in most cases.

Rainfall amounts received during the summer period (period 3) are very low, not exceeding 10% of the crop water needs for all stations, and irrigation is needed even for one year old plants.

For the period of September-November (period 4), *i.e.*, that of oil synthesis and harvest, annual water needs ranged between 62 and 215 mm following the age. Irrigation is necessary and particularly during the first weeks of this period particularly for Monastir, sidi Bouzid and Gabes where less than 60% of *ETc* of adult trees are covered.

Rainfall amounts received during winter (December-February, period 5) when flowers differenciate and fruits maturate cover more than 60% of young olive water needs even for the driest areas of Gabes and Sidi Bouzid. For Tunis, Béja, Bizerte and Nabeul, water needs are normally satisfied for all tranches of age.

4. Discussion

Aiming at a comparative analysis of the behaviour of the different methods of ET_0 computation, their performance against the ET_0-PM was evaluated in all considered cities through a set of commonly used statistics.

Results obtained from ET_0 estimation by using different formulas show that the response differs following site, season and the calculation procedure. Analyses of data on differences between ET_0 estimated with different formulas have shown that maximum estimates are provided by Eagleman and PO methods. The BC estimates are more often significantly superior to the other values. Minimum values are provided by ST and SW, Ivanov, Turc and Chr. Harg formulas depending on season and site. Significant differences were found between PO and PM-ET_0 estimates.

Values of ET_0 computed by different empirical formulas and compared to the PM-estimates using full datasets, show that the estimated ET_0 values strongly correlate with ET_0-PM at all stations with all formulas. However, the most appropriate methods are those of Turc and Ivanov, implying that these methods appropriately predict the ET_0 in all climatic regions of Tunisia. A visual inspection of data suggests that the Turc method performs well for all climatic zones, arid and semi-arid, in western, northern and coastal areas of Tunisia. The Ivanov method appears to be more appropriate to the northen areas *i.e.* Béja and Bizerte. Estimates of ET_0 by using the Hargreave-Samani (HS) equation for the east-southern area (Gabes) characterised by arid climate, show satisfactory agreement with PM-ET_0 value, though a poorer agreement was found when using the Eagleman formula.

Results presented herein are coherent with previous findings [5] [82] [100] [101] comparing several evapotranspiration methods, particularly those made in Iran [24] [30] [32] [86], reporting that the HS method performs well in most climatic regions, with the exception of humid areas where it tends to overestimate ET_0. The research works carried out around the Mediterranean basin show different responses. In Northern and Central Tunisia, Jabloun and Sahli (2008) [31] found better estimates for PM than for HS. Paredes and Rodrigues (2010) [102] found small errors with PM relative to HS, thus adopting it to estimate ET_0 in Portugal for irrigation scheduling purposes; they found that estimation errors were larger in humid locations comparative to dryer ones. Temesgen *et al.*, (2005) [100] stated that the HS method underestimates ET_0 for dry and windy locations due to not considering a wind factor and concluded that it is more accurate when applied for 5 or 7-day averages than for daily time scales. Application of PM to different climates of South Africa showed to be superior to HS and that better results were obtained when applied to 5-day rather than daily time cales [29]. Differently, Martinez and Thepadia (2010) [32] found that the HS produced smaller overestimation errors than PM in a humid climate, while Gocic and Trajkovic (2010) [22] proposed software to estimate ET_0 for minimizing computation errors using an adjusted HS equation when weather data are missing. Hargreaves and Allen (2003) and Razieia and Pereira (2013) [5]-[86] tend to explain these differences. Their explanation is based on a careful analysis of the history and applications of the HS equation, considering that as the HS method was developed initially for arid to sub-humid climates and thus it may not fit well to conditions of humid climates, necessitating different calibration with regard to the particularities of these climates. Droogers and Allen (2002) and Trajkovic (2007) [15] [103] attempted to recalibrate the HS coefficients in order to improve its performance. A large number of versions emerged to locally adapt the HS equation, amongst the PM which was lately adapted for using daily forecasted weather data for irrigation scheduling purposes [19]. However, Hargreaves and Allen (2003) [5] concluded that recalibrating the exponents and coefficients of the HS equation only increased the complexity of the equation. The HS method is usually preferred with respective to other more complicated equations since it requires only maximum and minimum air temperatures, which are available in most agro-climatic stations and can be measured with less error and by less trained individuals than the other climate variables used in combination equations. This is very important when solar radiation and wind speed data are lacking.

The consistent deviations of ET_0 estimations from the PM-ET_0 are supposed to be related to the effect of some climatic variables amongst the wind speed, which affect greately ET_0 computation. Discrepancies between HS and PM-ET_0 for example at Bizerte and Nabeul, is attributed to the high wind speed, particularly during spring when ET_0 is higher. In our case, the observed disagreement between estimations may be partially due to not considering wind speed in the HS method. In other case studies, errors may be due to the lack of data and the use of empirical formula for estimating wind speed [89]. Raziei and Pereira (2013) [86] showed that using seasonal regional values as default wind speed values decreased the variance of residuals and the heteroscedasticity of regressions but increased the regression coefficients and therefore ET_0 became over-estimated in the hot and windy locations (case of Bizerte and Nabeul). These authors conclude that, considering the need to minimize errors in estimating ET_0 when only temperature data are available in areas where wind may play a major role, remains an open problem to further research developments.

The BC formula correlates well with PM at all Tunisian sites with r values ranging between 0.888 and 0.927. However at seasonal scale it appears to be not appropriate for all growing periods. It performs well with PM during stages 1, 4 and 5 only for Nabeul and Sousse, which are coastal areas characterized by moderate rainfall amounts. These responses are perhaps due to the fact that the BC formula derived initially in farmers' fields under water stress conditions, and calculates an ET that is most closely related to the average county yields during the years the measurements were taken [104]. Therefore the values obtained in our case did not represent anon-water stressed condition. Razieia and Pereira (2013) [86] consider that the empirical relationship and the originally derived coefficients are nowadays outdated and invalid for today's agriculture production systems even with the subsequent changes that improved the BC-formula by adding more weather and crop variables, like that of Doorenbos and Pruitt (1974) [26] which is generally referred to as the FAO Blaney-Criddle (EtBC) including adjustment factors based on minimum relative humidity, sunshine, and daytime wind speed estimates. This modification to the BC formula was made to make it compatible with the modified Penman's reference ET equation.

Variations recorded when comparing the different methods of ET_0 estimation indicate that there is no weather-based evapotranspiration equation that can be expected to predict evapotranspiration perfectly under every climatic situation due to simplification in formulation and errors in data measurement. According to Razieia and Pereira (2013) [86] it is probable that precision instruments under excellent environmental and biological management conditions will show the FAO Penman-Monteith equation to deviate at times from true measurements of grass ET_0. However, the Expert Consultation agreed to use the hypothetical reference definition of the FAO Penman-Monteith equation as the definition for grass ET_0 when deriving and expressing crop coefficients.

Local information on K_c is scarce for olive, and mainly obtained from ET measurements by using the soil water balance method [76]. Orgaz *et al.*, (2006) [18] reported crop coefficients for olive varying from 0.45 to 0.75 in different locations which are far below the values of annual crops, typically varying from 1.0 to 1.2 [26]. For central Tunisia, Braham and Boussadia (2013) [96] found values of 0.46 during the flowering and fruit set periods. Villalobos *et al.*, (2000) [13] found an average annual crop coefficient of 0.62 which is considered rather low due to the low ground cover and to the enhanced control of canopy conductance by stomatal responses to VPD. These authors showed that the crop coefficient will vary among locations and even among years and seasons depending on soil humectation (rainfall, irrigation), solar radiation and reference evapotranspiration (ET), because this coefficient was derived under non-stressed conditions where water, fertilizer, insects, and salinity do not limit crop growth and production. However, in many cases these non-stressed conditions were not met when deriving the crop coefficients and consequently, the K_c values have been adjusted upward as new measurements of Et have occurred under better irrigation scheduling conditions in the research fields [27] [37].

The variability of K_c makes difficult to apply the FAO method to locations where no experimental information exists. So it is desirable to have a method that estimates directly the actual ET consistently well. In addition, the crop coefficient concept has not only the problem of it being unique to the reference ET formula use but the change in the crop coefficient over time can be a function of days since planting, percent cover or growing degree-days. Variations in K_c and *ETc* estimates are also inherent to differences in resistance to transpiration, crop height, crop roughness, ground cover and crop rooting characteristics which explain the different ET levels in different types of environmental conditions for identical crop. Thus the crop variety and development stage should be considered when assessing the evapotranspiration from crops grown in large, well-managed fields. Additional consideration should be given to the range of management practices that act on the climatic and crop factors affecting the ET process. Cultivation practices and the type of irrigation method can affect the crop characteristics and the wetting of the soil. These results indicate that the use of no adequate method to estimate reference evapotranspiration for *ETc* estimation allowed overestimating or underestimating the water requirements; future research is needed to reconcile which should be the standard method of calculating the change in the crop coefficient over time. Recent works on plant water use showed that integrating daily sap flow is a very good way to establish the connection between the reference evapotranspiration and the individual plant water use [51] [99]. The method was proven to be valuable and valid for canopies with different sizes, exposure and environments. Masmoudi-Charfi *et al.*, (2012) [105], by using the sap flow technique of Granier (1985) [91], found values of K_cxK_r of 0.53 for six-years old trees cultivated in North Tunisia, while Braham and Boussadia (2013) [96] adopting the same technique found specific values ranging between 0.46 and 0.51 for the period of flowing and early fruit development (April-May) for olive orchards cultivated in central Tunisia.This approach eliminates the need of the traditional crop coefficient scheme and future research is needed to reconcile which should be the standard method of calculating the change in the crop coefficient over time. It is desirable to have a method that estimates the (*ETc*) consistently well.

Results relative to rainfall distribution show large annual and seasonal variability. Precipitation occurs sporadically, particularly in the centre and southern areas. Annual precipitations computed, from 1901 to 2000 over 99 years long period varied from less than 200 mm at Gabes to more than 600 mm at Bizerte and Béja. The lowest amount was obtained for the regions of Sidi-Bouzid located at the Center of Tunisia in the western area.

At a seasonal scale, the rainiest periods are December-February for Béja-Tunis-Bizerte and September-November for the sites of Gabes, Sidi Bouzid, Sousse and Nabeul with similar trends for rainfall frequency. The autumnal and winter amounts are equivalent for Nabeul. The driest period is that of July-August for all sites. Minimum variations were observed during the summer period, in June (Nabeul, Sidi Bouzid) or July (Tunis, Sousse, Gabes) depending on site specificities.

On the basis of annual rainfall amounts and ET_0-Thornthwaite estimates, cities of study were classified by using the UNEP aridity index. Values show that Béja and Bizerte as well as Tunis, Nabeul and Sousse have semi-arid climate with IA ranging between 0.20 and 0.43, while Gabes and Sidi-Bouzid are characterized by typical arid-climate with IA of 0.11 and 0.15 respectively, in spite of their location, since Gabes is a coastal town and Sidi Bouzid a western area located at 314 m of altitude. These results show that Tunisia is not concerned with humid and sub-humid climates when the IA is considered to climatically classify these regions, although some published papers considered the region of Kroumirie, extreme NW of Tunisia as humid area [41], while arid and semi-arid climates dominate the central and southern landscape. Also, although Bizerte, a coastal region, has a relatively high annual precipitation accompanied with cold winters, it is not considered as a sub-humid region. Its AI is close to that provided for Béja, a continental area of NW Tunisia, situated at 144 m of altitude.

These conditions make yields of olive orchards highly dependent on rainfall amounts and specially their distribution, resulting in a recurring deficiency of soil moisture and variable yields. Indeed, olive production varies from one year to another by a factor of five depending on the amount of rainfall and fall's timing. This situation is uncomfortable for Tunisia because olive production is vital to national economy, playing a key role in maintaining social stability and accounts for a large share of employment (30 millions/year). To face this problem, adequate water conservation strategies have been developed since many centuries and most of them have focused on improving the performance of irrigation systems or on adapting crop management systems to reduce the need for irrigation water particularly during summer months. But, at this time, there was no any fundamental or technical research to determine the effective water needs of olive orchards. First studies begin in Tunisia during the seventeenths [64]. Yield-enhancing techniques have been adopted at different scales to ensure the best use of natural water resources, ranging from modern irrigation techniques (drip irrigation and fertigation) to high yielding cultivars grown with high levels of inputs and with densities ranging between 300 and more than 1250 plants/ha. Many research studies show that in environments characterized by alternating wet and dry seasons, adding small amounts of water during the growing season can increase remarkably water productivity [14] [40] [51] [52] [76] [85] [106]. However, this potential of supplemental irrigation must be explored to make better use of the limited resources available, how we can use this fresh water for irrigating olive species which is considered for a long time as a tolerant crop supporting water shortage, vegetating and producing even with very low amounts of water. Nowadays, orchadists, conscious that olive industry is an obvious choice to improve agriculture, take to be informed about the crop water management and how to determine precisely and judiciously water needs for a better use efficiency. To help orchardists, a technical paper has been prepared and widely distributed in 2006 [107], presenting the crop water needs of olive trees depending on soil coverage, age and sites of olive cultivation. In this paper the FAO-PM method was used to compute ET_0 with average climatic data recorded over a twenty-year long period.

Annual course of *ETc* computed with the PM method shows values ranging between 300 mm for young plantations and up to 800 mm for adult trees following. Highest *ETc* estimates are those recorded for Gabes, ranging between 335 mm and 894 mm depending on age. Minimum yearly values are recorded for Béja varying from 282 mm and 752 mm. Lysimetric values determined by Nasr (2002) [1] representing the effective need of water are lower than *ETc* computations (*ETc*-PM) for Tunis, Nabeul, Sousse and Gabes, which are coastal areas. Annual ratios between the lysimetric values and *ETc* range between 0.74 and 0.96 for these areas and approximate the unit for both Béja and Sidi Bouzid. At seasonal scale, results showed that *ETc* increases following season in response to the increasing leaf area, varying for all stations from 15 mm to 61 mm in March, from 87 mm to 254 mm for the coastal areas and from 90 mm to 266 mm for the continental locations from April to November. In most cases and particularly for adult plantations cultivated in Centre and South Tunisia, rainfall amounts didn't meet these water needs. Estimates of seasonal values of (*ETc*-P), showed negatives values. The deficit of water is present even for young plantations inspite of their low water needs. Rainfall amounts were unable to cover the needs of water for this specie during the period of May-September, *i.e.* during fruit growth, the most important period that determines the production level. These amounts should be supplied necessary by irrigation. The lowest deficit is that provided for Béja and the highest is observed for Gabes. At annual scale, values of (*ETc*-P) are positive for Tunis, Nabeul, Sousse, Bizerte and Beja when young olive plantations are considered. For adult trees, values are positive only for Tunis, Bizerte and Béja. This last location is the only case where water needs are covered for olive trees aged 6 to 10 years. So there is a need for irrigating olive plantations aging more than 5 years and especially when olive is cultivated in the western areas. Irrigation is needed during the growing fruit period but also during the other seasons, when shoots grow. It is also necessary during "on" and "off" years. On the other hand the curves relative to rainfall distribution established for the different periods of growing give precious quantitative and qualitative information about water supplies: how irrigation can be made and at which amounts. Indeed, it appears from these results based on the seasonal rainfall frequencies and water needs computed with the PM formulae that irrigation supply is necessary all time for trees aging more than 10 years even for the rainiest locations as Bizerte and Béja where 20% only of the water needs are satisfied by rainfall. For younger plantations, irrigation becomes necessary beginning from the second period of development, *i.e.* April-June for Bizerte, Béja, Nabeul and Tunis. For the other stations, and particularly for Gabes and Sidi-Bouzid, irrigation is necessary for both young and old trees during the early spring period. If the requested amounts are not applied, many problems can arise affecting shoot growth [54], root development, water mineral uptakes [108] [109], fructification [61], olive maturation [74] and production [73] [85] [110], but also the water use efficiency. However, recent studies show that we can reduce water supplies during some periods without affecting production or fruit size, through application of the *concept of deficit irrigation* [50] [55] [56] [111]-[115]. Furthermore, a certain lack of water is appreciated and can improve substantially fructification and oil synthesis, but only if water is applied at specific stages [60] [116].

5. Conclusions

Based on a careful analysis of the history and applications of empirical formula for ET_0 computation, their accuracy have been assessed against the ET_0-PM formula, showing an adequateness of using some of them in Tunisia for different climatic sites. Good relationships were observed between ET_0-PM estimates and those issued from Ivanov, Turc and HS methods, confirming the previous referred conclusion, which indicates that ET_0 can be estimated with a specific formula even when climatic data are lacking. Each region may have an appropriate alternative for ET_0 estimation. This may concern even the remote stations having only minimum and maximum temperature records.

Adequate estimation of ET_0 is of great importance in agricultural and hydrological studies, water resources and watershed management. In particular, it is required for supporting irrigation scheduling, drought management and climate change studies. In this work, irrigation water needs of olive obtained from ET_0-PM computation were determined following sites of olive production, age of the orchard and the growing periods by associating them to the rainfall distribution functions. This allowed us to determine the case studies where irrigation is needed. However, despite a quite good performance of the PM-equation in most applications, and the fact that it is appropriate for a wide range of climates and sites, particularly when it is used for *ETc* estimation and irrigation scheduling purposes, using this method may confront users with the lack of information on radiation and *ETc*. It is thus necessary to adjust them with regard to the local conditions, and particularly in precising the correct values of *ETc*, which should be determined for all growing periods because the crop coefficient concept has not only the problem of it being unique to the reference ET formula use but the change in *ETc* values over time can be a function of days since planting, percent cover soil, humectation, vapour pressure deficit (VPD), solar radiation. Additional research is needed on developing specific crop coefficients that use the PM-equation when calculating ET and a standardized method of calculating the time base for the crop coefficients preferably based on a growing degree day concept. Also, applying irrigation amounts on the basis of ET_0-PM formula needs necessary determination of the effective rainfall amounts which is not easy to measure and many studies use approximate method for its calculation. It remains a big challenge.

Herefore, to have a reliable estimation of ET_0 at a fine spatial resolution over the country, it is important to use accurate methods requiring limited weather data that can be available in a dense network through the country as it is the case for temperature. Indeed, the stations recording the climate variables needed for ET_0-PM estimation are very sparse and in many cases have incomplete records, particularly in the central and southern areas where the Tunisian deserts are situated. That's why to our best knowledge, this work with that of Nasr (2002) [1] is the only one that has estimated ET_0 for the whole country, but we didn't test the possible advantages in using calibrated values for the radiation adjustment coefficient or temperature adjustment for dew point temperature estimation as proposed by Allen (1996) [2]. This calibration is therefore a line to be explored.

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List of Abbreviations

ASCE: American Society of Civil Engineers Standardized Reference ET equation.
BC: Blaney-Criddle formula for ET_0 computation.
$\mathbf{c_p}$: specific heat of the air.
$\mathbf{C_{TT}}$, $\mathbf{C_{WT}}$, $\mathbf{C_{HT}}$, $\mathbf{C_{ST}}$, $\mathbf{C_R}$: functions of temperature, wind, relative humidity, insulation and elevation.
Chr. **Harg**.: Christiansen-Hargreaves method for ET_0 computation.
$\mathbf{e_o}$: saturation vapor pressure (kPa).
e_a: actual vapor pressure (kPa).
$e_o - e_a$: vapor pressure deficit of the air (kPa) and e_a is actual vapor pressure (kPa).
$e_o = 0.5[e_o\{T_{max}\} + e_o\{T_{min}\}]$ and $e_a = [e_{oTmax} RH_{min} + e_{oTmin} RH_{max}]/200$.
$\mathbf{ET_0}$: Reference evapotranspiration (mm/day).
$\mathbf{ET_0}$**-PM or PM-**$\mathbf{ET_0}$: Reference evapotranspiration obtained from Penman-Monteith equation (mm).
ETc: Crop evapotranspiration (mm).

***ETc*-PM**: Crop evapotranspiration calculated on the basis of ET_0 Penman-Monteith computation (mm).
***ETc*-P**: Climatic water deficit (mm).
ET: Maximum daily, monthly or seasonal evapotranspiration determined under non-stressed conditions (mm).
E: Elevation.
EAG: Eagleman method for ET_0 computation.
F: Rainfall frequency (%).
FAO-PM: Penman-Monteith method of FAO.
G: Soil heat flux density ($MJ \cdot m^{-2} \cdot day^{-1}$), flux of heat into the soil, set equal to zero to represent the condition of an isolated tree.
RH_{max}, RH_{min} and $RH_{average}$: Maximum, minimum and average air humidity.
HS: Hargreaves-Samani formula for ET_0 computation.
IA: Index of aridity.
INM: National Institute of Meteorology of Tunisia.
ETc: Crop coefficient.
K_r: coefficient introduced to take into account the soil coverage.
LAI: Leaf area index.
N: Maximum sunshine durations (hours/day).
n: Actual sunshine durations (hours/month).
p: daylight hours monthly/annual daylight hours.
i: number of days/month.
P: Rainfall amount (mm)
PM: Penman-Monteith equation.
PMT: Penman Monteith Temperature method.
PO: Penman Original method for ET_0 computation
r_s and r_a: bulk surface and aerodynamic resistances.
R_a: atmospheric radiation ($Mj/m^2/day$).
R_n: net radiation at the crop surface ($MJ \cdot m^{-2} \cdot day^{-1}$), R_n is computed as the algebraic sum of the net short and long short radiations.
ST and SW: Hargreaves-Samani method for ET_0 computation.
T: Tree transpiration (liters of water/day or mm).
T: Mean daily air temperature at 2 m height (˚C), u_2 is wind speed at 2 m height ($m \cdot s^{-1}$),
T_{max} and T_{min}: maximum and minimum air temperatures (˚C),
T_m or $T_{average}$: Mean daily air temperature ˚C, with T: ˚F = (T x 9/5) +32 with $T_{mean} = 0.5 (T_{max} + T_{min})$
ΔT: $T_{max} - T_{min}$.
TW: Thornthwaite method for ET_0 computation.
U_2: wind speed measured at 2 m height (m/s).
VPD: vapour pressure deficit (kPa).
Δ: Slope of the saturated vapor pressure curve ($kPa \cdot {}^{\circ}C^{-1}$).
γ: Psychrometric constant ($kPa \cdot {}^{\circ}C^{-1}$), was set constant and equal to 0.066 $kPa \cdot {}^{\circ}C^{-1}$ for all experiments.
Months:
Sept.: September.
Nov.: November.
Dec.: December.
Feb.: February.