

EVALUATION OF DIFFERENT METHODS FOR CALCULATING POTENTIAL EVAPOTRANSPIRATION IN DROUGHT SEVERITY ASSESSMENT

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ABSTRACT

The most common approach for drought severity assessment is through the calculation of drought indices. Popular drought indices are either of a complex nature, demanding a large number of parameters for their calculation (e.g. PDSI), or of a simple nature that usually disregard significant conditions that are contributing in the estimation of water resources availability in an area (e.g. SPI). However, in a changing climate, it is essential to use an index that can remain simple regarding data requirements and its calculation, but at the same time include other significant parameters apart from precipitation. Therefore, the Reconnaissance Drought Index (RDI) which is using precipitation and potential evapotranspiration (PET), the easiest additional significant determinant that should be included, is considered as an appropriate choice for drought severity assessment under climatic change. However, different methods for calculating PET may lead to different results, which in turn may affect the calculated RDI values. In this paper some widely accepted methods for estimating PET (Penman-Monteith, Hargreaves, Thornthwaite and Blaney-Criddle) are used and evaluated for areas of the Mediterranean region, using statistical indicators such as the root mean square error (RMSE) and the mean bias error (MBE). In order to compare the performance of each method, data from selected stations of Greece were used. RDI is calculated using the results of the proposed methods and the different RDI values are compared to each other. The most appropriate methods for estimating PET, which should be used for drought severity assessment through RDI, are proposed.

1 INTRODUCTION

In a climate change era, drought severity assessment should include at least the determinant of evapotranspiration in order to provide more accurate results but at the same time keep data requirements to the minimum. This is achieved through Reconnaissance Drought Index (RDI) which is using precipitation along with potential evapotranspiration. Since evapotranspiration can be estimated by various methods, differences in PET values may lead in different RDI values, creating a confusion regarding the applicability of the drought index in the widest possible range of cases.

This paper investigates the effect of calculation of potential evapotranspiration using various widely accepted methods in the final results of the drought index. The objective is either to produce evidence of the robustness of RDI values regardless the equation used for the estimation of evapotranspiration, or choose the appropriate method of estimating evapotranspiration that should be used for the calculation of RDI.

The evaluation of the four selected methods will be achieved through statistical analysis tools. An attempt to present the evapotranspiration estimation methods will be made so as the RDI user will be aware of the possible deviations in RDI results in the cases that a specific PET calculation method has to be used (e.g. due to data limitations).

2 METHODOLOGICAL COMPONENTS

2.1 Estimating evapotranspiration

Evapotranspiration is a key component of the hydrological cycle. The evaluation of evapotranspiration is an important aspect in the study of the impact of climate change on water resources, since it is a “key link” between the atmosphere and the soil matrix within the hydrologic cycle. Any estimate of climate change impacts on water resources depends on the ability to relate changes in actual evapotranspiration to predicted changes in precipitation and potential evapotranspiration (Yates and Strzepek, 1994). In order to achieve proper predictions in evapotranspiration changes, good estimates of the driving mechanisms of that change are considered an important starting point.

A number of approaches have been used worldwide to assess evapotranspiration. These evaluation methods can be divided into three main categories: hydrologic or water balance methods, analytical methods based on climate variables, and empirical estimates. The first category comprises physically based approaches and its use in climate change assessment is limited to the laboratory. In the second category, evaporation and transpiration processes are described through mathematical relationships which focus on two main climatological components, the energy balance and the mass transport. The Penman-Monteith and the Priestly-Taylor equations are well known examples in this category. Finally, the empirical methods are mainly based on temperature and became very popular due to their limited data requirements. Their disadvantage is that in most of the cases they are site specific (based on local climatological conditions) and they often need to be “calibrated” by relating their estimates to observed measurements. However, since they provide good estimates and the data that they require are available almost everywhere, they are used widely in evapotranspiration assessment. Methods in this category are the well known Hargreaves, Thornthwaite and Blaney-Criddle equations.

In this paper, methods of both the second and the third category are used to estimate potential evapotranspiration. The aim is not only to compare the performance of the methods in the Mediterranean conditions, but mainly to assess the influence of the different estimations in drought severity assessment. To achieve this goal, the sensitivity of the Reconnaissance Drought Index – RDI (Tsakiris and Vangelis, 2005) to these differences will be evaluated. The methods that are evaluated are the following.

The FAO Penman-Monteith method: The method which is nowadays recommended as the standard method for determining evapotranspiration was initially proposed in

1948 by Penman, who combined the energy balance with the mass transfer method and derived an equation to compute the evaporation from an open water surface, from standard climatological records of solar radiation (sunshine), air temperature, humidity and wind speed. This method was further developed by many researchers and extended to cropped surfaces by introducing resistance factors.

In May 1990, a panel of experts and researchers was organised by FAO in collaboration with the International Commission for Irrigation and Drainage and the World Meteorological Organisation, in order to review the methodologies on crop water requirements and to propose revisions and updates of procedures. The panel recommended the method which is known as FAO Penman-Monteith method to estimate evapotranspiration (Allen et al., 1998), which is derived by the equation:

$$PET = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where R_n is the net radiation at the crop surface ($\text{MJ/m}^2\cdot\text{day}$), G is the soil heat flux density ($\text{MJ/m}^2\cdot\text{day}$), T is the mean daily air temperature at 2 m height ($^{\circ}\text{C}$), u_2 is the wind speed at 2 m height (m/s), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), $e_s - e_a$ is the saturation vapour pressure deficit (kPa), Δ is the slope vapour pressure curve ($\text{kPa}/^{\circ}\text{C}$) and γ is the psychrometric constant ($\text{kPa}/^{\circ}\text{C}$).

The FAO Penman-Monteith equation was developed by defining the reference crop as a hypothetical crop with an assumed height of 0.12 m having a surface resistance of 70 s/m and an albedo of 0.23, actively growing and adequately watered.

The Thornthwaite method: One of the most widely used methods is the one proposed by Thornthwaite (1948). Though there are several studies which show that the method underestimates evapotranspiration, it is widely applicable around the world often used with a multiplying coefficient to increase its relative magnitude. The method estimates evapotranspiration based on the following equation:

$$PET = 16 \cdot \left(\frac{N}{12}\right) \cdot \left(\frac{m}{30}\right) \cdot \left(10 \cdot \frac{T_{mean}}{I}\right)^a \quad (2)$$

where T_{mean} is the mean monthly temperature ($^{\circ}\text{C}$), N is the mean monthly possible sunshine hours (h/day) and m is the number of days of each month and a is given by the equation:

$$a = 6.75 \cdot 10^{-7} \cdot I^3 - 7.71 \cdot 10^{-5} I^2 + 1.79 \cdot 10^{-2} I + 0.49 \quad (3)$$

Finally I is a heat index calculated as the summation of the 12 monthly values according to the following equation:

$$I = \sum_{i=1}^{12} \left(\frac{T_{i,mean}}{5} \right)^{1.514} \quad (4)$$

The Hargreaves method: The Hargreaves equation is another temperature based empirical method. Hargreaves was asked in 1948 by the Bureau of Reclamation to prepare a manual on using E_p and ET_c in the planning and design phases of the Central

Valley Project. Since then a lot of attempts to estimate crop evapotranspiration were made based upon measured or estimated E_p , modifications to Blaney-Criddle method or on versions of or simplifications to a method developed by J.E. Christiansen (Hargreaves and Allen, 2003). Finally, in 1975 Hargreaves published the following equation:

$$PET = 0.135 \cdot R_s \cdot (T_{mean} + 17.8) \quad (5)$$

where R_s is the global solar radiation at the surface (mm/day) and T_{mean} is the mean temperature (°C).

Since R_s was not easily available and after the analysis of climate data and review of the literature Hargreaves concluded that R_s could be computed from extraterrestrial radiation (R_a) and the percentage of possible sunshine (S). After a lot of research Hargreaves and Samani (1982) proposed the predictive form:

$$R_s = K_{RS} \cdot R_a \cdot TR^{0.50} \quad (6)$$

where K_{RS} is an empirical coefficient fitted to R_s/R_a versus TR data, while TR is the daily temperature range in Celsius degrees ($TR = T_{max} - T_{min}$; where T_{max} is the mean daily maximum temperature and T_{min} is the mean daily minimum temperature).

Combining the two previous equations and using $K_{RS}=0.16$ (a value obtained by climatic data from the Senegal River Basin) Hargreaves et al. (1985) obtained the equation:

$$PET = 0.0022 \cdot R_a \cdot (T_{mean} + 17.8) \cdot TR^{0.50} \quad (7)$$

However, Hargreaves and Samani (1985) recommended that the coefficient should be increased to take into account the months of the peak demand, which resulted in the so-called 1985 Hargreaves equation:

$$PET = 0.0023 \cdot R_a \cdot (T_{mean} + 17.8) \cdot TR^{0.50} \quad (8)$$

The attractiveness of the method lies on its simplicity, reliability, minimum data requirements, ease of computation, and low impact by weather station aridity (Hargreaves and Allen, 2003).

The Blaney-Criddle method: Blaney and Criddle equation is one of the earliest equations for estimating evapotranspiration involving the use of temperature. Though the method is widely used as it has been modified by Doorenbos and Pruitt (1977), the usual form of the equation is written as:

$$PET = k \cdot p \cdot (0.46 \cdot T_{mean} + 8.13) \quad (9)$$

where T_{mean} is the mean temperature (°C), p is the percentage of total daytime hours for the period used (daily or monthly) out of total daytime hours of the year and k is a monthly consumptive use coefficient, depending on vegetation type, location and season.

The value of p is usually obtained by tables; however it can be estimated for specific latitude using the following equation:

$$p = 100 \cdot \left(\frac{\sum_{i=d_1}^{d_2} N_i}{\sum_{i=1}^{365} N_i} \right) \quad (10)$$

where N_i is the theoretical daytime hours of the Julian day i and d_1 and d_2 are the first and the last Julian day of the month.

According to Blaney and Criddle the coefficient k varies for the growing season (May to October) from 0.5 for orange tree to 1.2 for dense natural vegetation (Xu and Singh, 2001). In this paper, an average value of 0.85 will be used since the study is aiming to methodology comparison regardless specific cultivating procedures.

2.2 Drought severity assessment

Drought severity will be assessed through the computation of Reconnaissance Drought Index (RDI) and more significantly through the standardised form of RDI. The calculation of RDI_{st} can be performed by fitting the gamma probability density function (pdf) to the given frequency distribution of the initial value (a_k) of RDI (Tsakiris et al., 2008; Tigkas, 2008). Positive values of RDI_{st} indicate wet periods, while negative values indicate dry periods compared with the normal condition of the area. The severity of drought events increases when RDI_{st} values are lower. Drought severity can be categorised in mild, moderate, severe and extreme levels, with corresponding thresholds of RDI_{st} (-0.5), (-1.0), (-1.5) and (-2.0), respectively (Tsakiris et al., 2010). RDI is calculated for a hydrological year in monthly, seasonal or annual basis. In this study annual RDI values are used.

For comparison reasons the widely used Standardised Precipitation Index – SPI (McKee et al., 1993; McKee et al., 1995) will be also evaluated.

2.3 Statistical analysis tools

In order to comparatively evaluate the different methods for estimating evapotranspiration, two widely used statistical indicators will be used: the Root Mean Square Error (RMSE) and the Mean Bias Error (MBE).

The RMSE is computed according to the following equation:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (PET_{est,i} - PET_{obs,i})^2} \quad (11)$$

providing information on the short term performance. The value of RMSE is always positive, represented as “zero” in the ideal case (Yapo et al., 1998).

The MBE is computed according to the following equation:

$$MBE = \frac{1}{n} \sum_{i=1}^n (PET_{est,i} - PET_{obs,i}) \quad (12)$$

providing information on the long term performance of the correlations by allowing a comparison of the actual deviation between predicted and measured values term by term. The ideal value of MBE is “zero” (Gunhan et al., 2005).

In both equations, n is the total number of observations, PET_{est} is the estimated PET by each method and PET_{obs} is the value computed by the method used as reference in each case.

3 RESULTS AND DISCUSSION

In order to test the influence of different estimations of evapotranspiration, which are produced by the various methods used, in the values of RDI, data from two meteorological stations of Greece were used. These stations were selected in order to fulfil two major requirements: to have records of adequate time length of as many meteorological parameters possible, in order to be able to use all the selected methods; and to represent different climatic conditions within the Mediterranean climatic context. The first meteorological station, called “Aspropotamos”, is located in a high altitude (1050 m) mountainous forested area, while the second station, called “Heraklion” is located in a low altitude (39 m) plain, coastal area. For both stations, monthly data of precipitation, maximum and minimum temperature, relative humidity and wind speed were available.

As a first step, the data of both stations were tested for their validity and cross-checked with data of neighbouring stations. In a very few significant cases data points were corrected and measurement gaps were filled in, in order to produce long but robust time series. All the corrections were made according to hydrological, meteorological and statistical methodologies, resulting to a 30-year data series for the Aspropotamos station and a slightly longer (46-year) data series for the Heraklion station. Then, potential evapotranspiration was calculated by the four methods earlier presented for both stations. Additionally, PET was calculated by the Penman-Monteith equation using only temperature data (T_{min} and T_{max}) as described by Allen et al. (1998). The results of the calculations are illustrated in Figures 1 and 2 for each of the two stations.

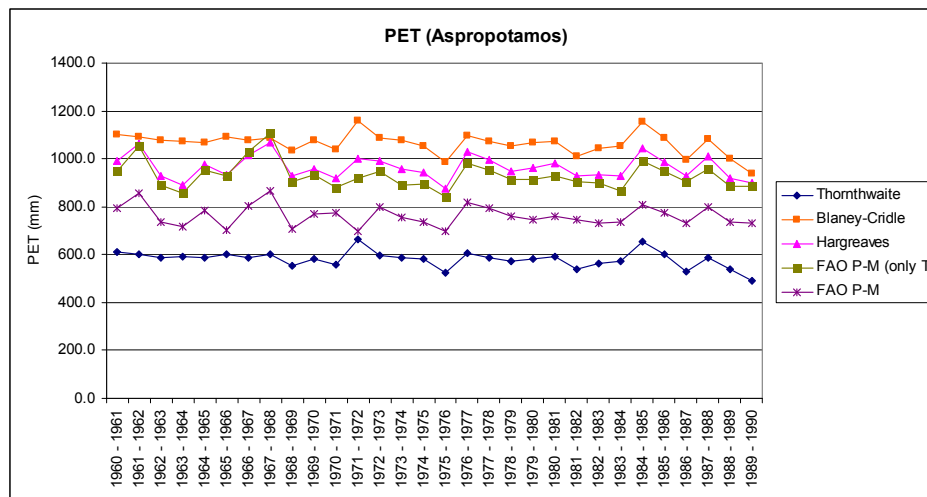


Figure 1. Potential evapotranspiration calculated by various methods for Aspropotamos station.

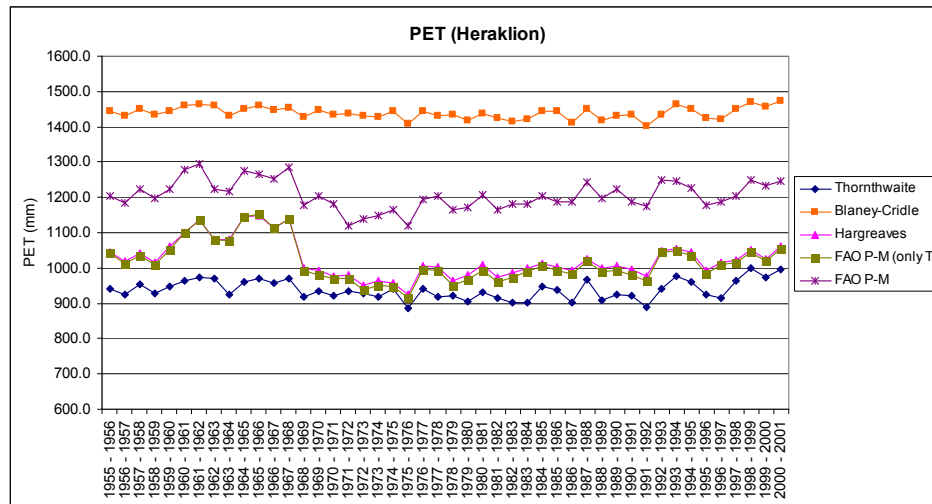


Figure 2. Potential evapotranspiration calculated by various methods for Heraklion station.

The PET results presented in Figures 1 and 2 could be considered more or less expected. In both stations, the Thornthwaite equation produces the lower values, while the Blaney-Cridle equation the higher ones, with a difference of about 500 mm in mean values. Another interesting point is that these two equations follow the same yearly pattern, with similar fluctuations around their mean values in the same time points. On the other hand, a different fluctuation pattern is followed by the other two equations (Penman-Monteith and Hargreaves). The difference between the two stations is that in Aspropotamos case the Hargreaves equation gives higher values than the Penman-Monteith equation, while in Heraklion the opposite situation is observed. Finally, an interesting observation is that in the case of using only temperature data in the Penman-Monteith equation (presented as “FAO P-M (only T)” in the Figures) as advised by FAO for the case of lack of data, the PET values produced are very close to the values given by the Hargreaves equation, while for a short period of years at the Heraklion station the values given by the two equations are almost identical.

At this point, a statistical evaluation of the equations will be performed, though this paper does not aim in evaluating the methods for estimating PET, but their effects in RDI calculation. However, in order to perform the statistical tests, a set of PET values should be used as a base for the comparisons. Since there are no available measured data (e.g. lysimeter data) at the areas under study, values produced by one of the methods should be considered as the base of comparisons, a choice that will be mainly based in literature. A number of studies (Ventura et al., 1999; Yoder et al., 2005; Lopez-Urrea et al., 2006) indicate that the FAO Penman-Monteith equation is performing better than other methods when evaluated against lysimeter data, while other studies consider it as “highly recommended” and use it as the base for comparisons anyway (Xu and Singh, 2002; Pereira and Pruitt, 2004; Trajkovic and Kolakovic, 2009). Although there is also evidence that the FAO Penman-Monteith equation does not always provide the best results (Douglas et al., 2009), it will be used as the base method in this study. The RMSE and MBE statistical indicators calculated for each station using

the FAO Penman-Monteith results as observed values are presented in Table 1.

Table 1. Statistical comparison of the evapotranspiration estimation equations.

Meteorological Station	PET estimation equation	RMSE	MBE
Aspropotamos	Hargreaves	204.3	202.6
	Thornthwaite	186.4	-181.2
	Blaney-Criddle	305.8	301.9
	FAO P-M (only T)	171.4	168.8
Heraklion	Hargreaves	183.5	-189.1
	Thornthwaite	269.3	-267.9
	Blaney-Criddle	235.4	233.3
	FAO P-M (only T)	191.3	-189.4

The statistical analysis seems to confirm the findings already presented. Table 1 illustrates through MBE the underestimation or overestimation of evapotranspiration values through the used methods in comparison to the FAO Penman-Monteith equation, as well as the magnitude of the differences among the methods. It is worth observing that the MBE values at Heraklion station for the Hargreaves and FAO P-M (only T) methods are exactly the same.

The next step is the calculation of RDI by the use of the evapotranspiration values produced by the various methods. Both the initial form of RDI (a_{12}) and the standardised form RDI_{st} were calculated with the use of DrinC software (Tsakiris et al., 2007). Since the performance of RDI_{st} is the main objective of this study, the main conclusions will be derived by the RDI_{st} which is presented for the two stations in Figures 3 and 4. The statistical analysis based on the same indices used for the evapotranspiration estimation methods is also performed for the RDI_{st} values (Table 2).

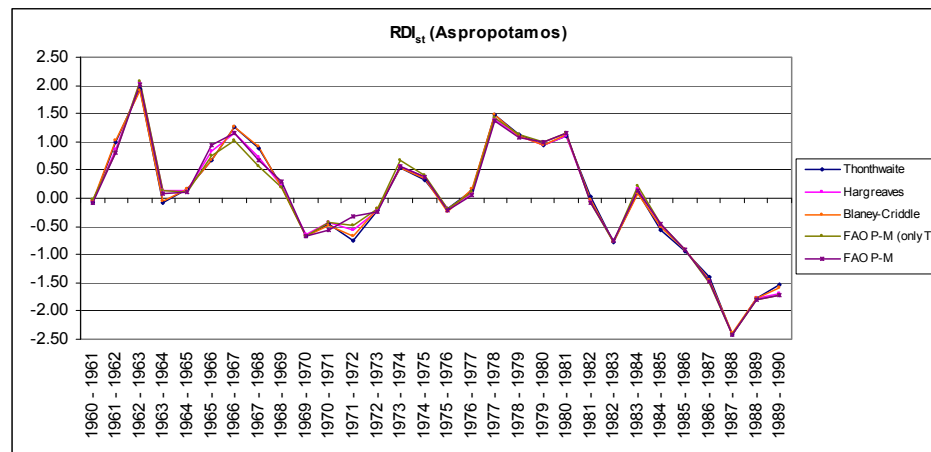


Figure 3. RDI_{st} values calculated for the different PET estimations (Aspropotamos station).

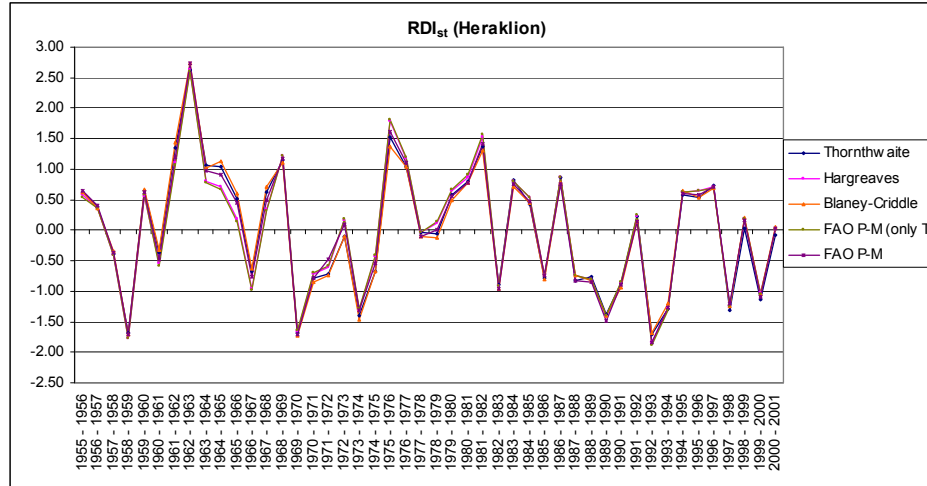


Figure 4. . RDI_{st} values calculated for the different PET estimations (Heraklion station).

Table 2. Statistical comparison of the RDI_{st} values calculated for the various evapotranspiration estimation equations.

Meteorological Station	PET estimation equation	RMSE	MBE
Aspropotamos	Hargreaves	0.06	$-1 \cdot 10^{-4}$
	Thornthwaite	0.13	$-6 \cdot 10^{-4}$
	Blaney-Criddle	0.12	$-5 \cdot 10^{-4}$
	FAO P-M (only T)	0.07	$-1 \cdot 10^{-4}$
Heraklion	Hargreaves	0.10	$2 \cdot 10^{-5}$
	Thornthwaite	0.09	$4 \cdot 10^{-5}$
	Blaney-Criddle	0.11	$2 \cdot 10^{-6}$
	FAO P-M (only T)	0.11	$3 \cdot 10^{-5}$

As shown by the above Figures, RDI_{st} values are almost identical regardless the method used for the estimation of evapotranspiration. Slight differences which appear in a few time points can not be considered significant, since they do not affect drought severity reported by the index. The various values in spite of their differences remain in the same drought severity zone without exceeding any drought severity threshold as defined by RDI. An important aspect is that the Heraklion case presents far more drought episodes along with higher evapotranspiration values than Aspropotamos case. The statistical analysis, on the other hand, proves that on the long term performance (as presented by MBE) the various RDI_{st} datasets are identical, while on the short term performance (as presented by RMSE) they are also almost identical, since the slight deviation of RMSE values from the ideal “zero” can not be considered significant. It should be also mentioned that regression analysis against SPI values produces correlation coefficients over 0.9 for all of the cases.

According to these results, the authors would propose the use of any of the tested evapotranspiration equations for the calculation of RDI_{st}. However, the Hargreaves

equation provides values closest to the values produced by the widely accepted FAO Penman-Monteith equation and almost identical values to the FAO P-M equation which uses only temperature data. Moreover, Hargreaves results correlate better with FAO P-M results in relation to the other methods following the same fluctuation pattern. Since RDI aims mainly in utilising the important element of evapotranspiration but keep data requirements to the minimum, Hargreaves equation seems the best choice for estimating evapotranspiration for the calculation of RDI.

In the case that the initial value of RDI, a_{12} should be used (e.g. in order to compare the magnitude of drought against the aridity index) the choice may be different.

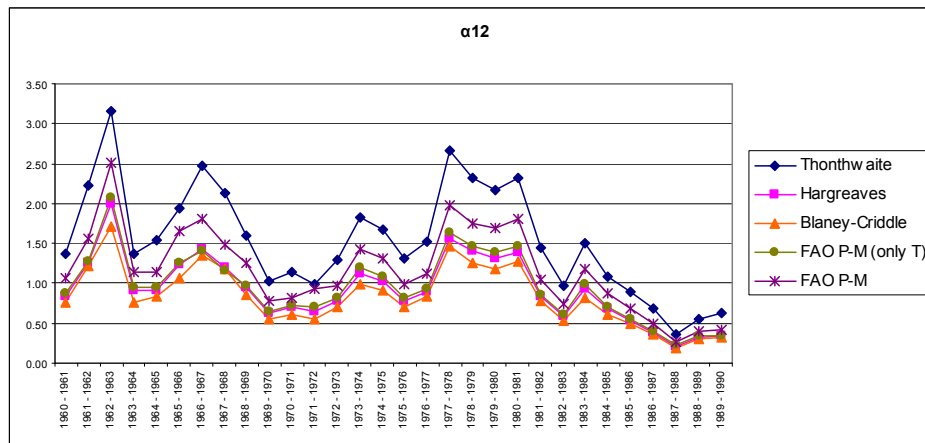


Figure 5. Initial RDI (a_{12}) values calculated for the different PET estimations (Aspropotamos station).

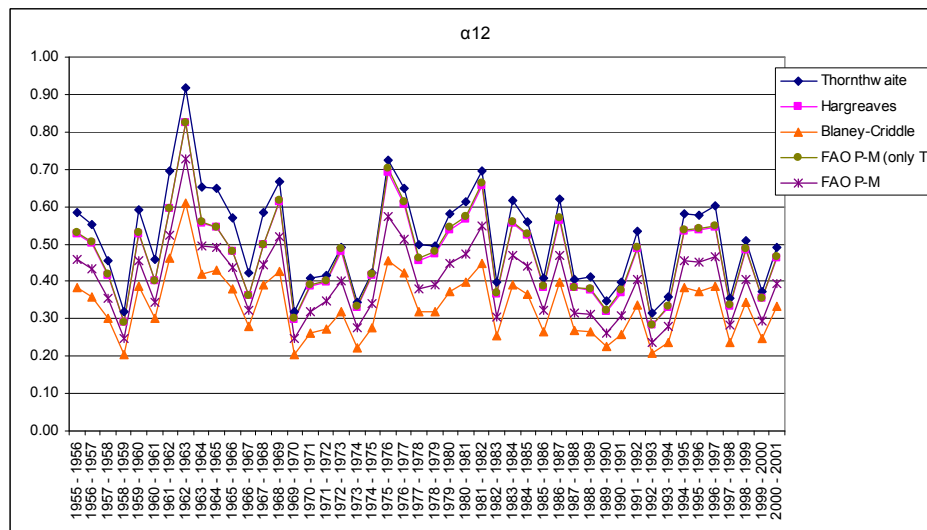


Figure 6. Initial RDI (a_{12}) values calculated for the different PET estimations (Heraklion station).

As shown by Figures 5 and 6, a_{12} values have proportional differences with the values produced by the various evapotranspiration methods. In this case, FAO Penman-Monteith equation may be used for more accurate results. However, if data availability is limited, Hargreaves equation may also be used for the same reasons explained earlier in this paragraph.

4 CONCLUSIONS

In the era of climate change, the Reconnaissance Drought Index (RDI), which incorporates the use of evapotranspiration, provides a sound theoretical base for the drought severity assessment. However, the results of RDI face the risk of being affected by the potential evapotranspiration (PET) estimations since they can be calculated by various methods, creating confusion in drought severity assessment.

In this study, values produced by four methods for estimating evapotranspiration have been used for the calculation of RDI_{st} . Illustration of the RDI_{st} values produced as well as statistical analysis on these values show that there is no remarkable difference in RDI_{st} values regardless the evapotranspiration equation used. However, since RDI aims to be a robust but low data demanding drought index, Hargreaves equation seems to be the most appropriate choice for estimating PET values for the calculation of RDI_{st} .

Hargreaves equation is chosen mainly due to the following facts. FAO Penman-Monteith equation is widely accepted for the estimation of PET, however it is a highly data demanding method, using data that are not easily available in every place of the world. Hargreaves estimates correlate better and have the smaller deviation with FAO P-M values than the results of the other equations tested and almost identical results in the case that only temperature data are used with the FAO P-M equation in both a forested mountainous and a plain coastal environments.

Acknowledgments. The authors would like to thank the Forest Research Institute of Athens and Dr N. Proutsos for pre-processing and kindly providing the data of Aspropotamos station.

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