ESTIMATING POTENTIAL EVAPOTRANSPIRATION AND ITS SPATIAL DISTRIBUTION IN GREECE USING EMPIRICAL METHODS.

PAPADOPOULOU E., VARANOU E., BALTAS E., DASSAKLIS A., and MIMIKOU M.

National Technical University of Athens, Faculty of Civil Engineering,
Department of Water Resources, Hydraulic and Maritime Engineering

EXTENDED ABSTRACT

This paper studies the potential evapotranspiration and its spatial distribution for the 10 out of the 14 water districts of Greece. The estimation of potential evapotranspiration is achieved by adopting empirical approaches, such as the Thornthwaite equation, the Blaney-Criddle formula and the Hargreaves method, all having as a requirement the availability of temperature data. The data set is made up of temperature time series, obtained from 137 gauging stations operated by the Ministry of Environment, Planning and Public Works, the Ministry of Agriculture, the National Meteorological Service, the Public Power Corporation and the National Observatory of Athens. The raw data are analysed and processed on a monthly time step. The Thornthwaite equation and the Blaney-Criddle formula are applied to the 10 out of the 14 water districts of the country, while the Hargreaves method is applied in the water district of Western Macedonia. The potential evapotranspiration estimated for each station using the above-mentioned methods is spatially integrated, in order to obtain the areal potential evapotranspiration. The methods adopted for the spatial integration of the point estimates are the Kriging method, the method of Inverse Distance Weighting, the Spline method and the Thiessen method, using applications in a Geographic Information System (GIS) with a spatial resolution of 200x200m^2. It was found that for the Thornthwaite and Blaney-Criddle methods, potential evapotranspiration is slightly larger in the eastern part of the country. Furthermore, the Thornthwaite method produced smaller values (ranging from 10 to 20%), compared to the Blaney-Criddle method. Finally, the Hargreaves method that was applied only in the water district of western Macedonia, overestimates potential evapotranspiration by approximately 30% and 12%, compared to the potential evapotranspiration estimated by the Thornthwaite and Blaney-Criddle methods respectively.

Keywords: Potential evapotranspiration, Thornthwaite method, Blanney-Criddle method, Hargreaves method, Geographic Information Systems, spatial integration

1. INTRODUCTION

According to Thornthwaite's definition (1943), potential evapotranspiration (PET) is "water loss which will occur if at no time there is a deficiency of water in the soil for use by vegetation". Evapotranspiration is a very important component of the hydrologic budget. It varies regionally and seasonally. Because of this variability, water managers responsible for planning and adjudicating the distribution of water resources need to have a thorough understanding of the evapotranspiration process and knowledge about its spatial and temporal fluctuation (Hanson, 1991). As water demand by the agricultural sector in Greece exceeds 80% of the total, the need for reliable estimation of evapotranspiration is

obvious. The de-facto standard method for estimating potential evapotranspiration, the Penman-Monteith equation, is relatively high data demanding and sensitive to data that are difficult to measure. Therefore, in the absence of adequate raw data (as is the case for Greece), elaboration of the current paper focuses in the estimation of potential evapotranspiration for most water districts of Greece, by employing empirical methods. The adopted methods for the estimation of potential evapotranspiration were the Thornthwaite and Blaney-Criddle methods, while the Hargreaves method was also employed for the water district of western Macedonia. The minimal data requirements of these methods render them very useful for Greece.
The study used of timeseries of monthly temperature, obtained from 137 gauging stations of Greece that constitute the meteorological network of such organizations as the Ministry of Environment, Planning and Public Works, the Ministry of Agriculture, the National Meteorological Service, the Public Power Corporation and the National Observatory of Athens. All relevant information was readily available in the National Data Bank of Hydrological and Meteorological Information (NDBHMI). NDBHMI is a database system particularly important for the management of the country's water resources, as it contains raw and processed hydrometeorological and hydrological data for the whole of Greece, and a GIS environment containing the corresponding geographical information. The distributed database project includes data from over 2500 hydrometeorological and hydrometric gauging stations, while various software applications have been developed and are linked to the central database, supporting several analysis options for the stored data.

2. POINT ESTIMATION OF POTENTIAL EVAPOTRANSPIRATION

2.1. Thornthwaite method

Thornthwaite's method calculates potential evapotranspiration using observed air temperature and duration of sunlight data. The rationale is that air temperature does, to a considerable extent, serve as a parameter of the net radiation. This is a shortcut of replacing a comprehensive atmospheric model, as well as some interactions by prescribing observed temperature and precipitation (Huang et al., 1996).
This method for estimating PET requires only two variables; mean monthly temperature values, and the average monthly number of daylight hours. The following formula is applied for the calculation:

$$E = 16 * (10T/I)^a * \mu N/360 \qquad (1)$$

where:

- E is monthly potential evapotranspiration (mm/month),
- T is mean monthly temperature (^oC),
- I is an empirical annual heat index, the sum of 12 monthly index values i. The value of i for each month is derived from mean monthly temperatures according to the formula: $i_j = 0.09*(T_j)^{1.5}$, where subscript j indicates the specific month under investigation,
- μ is the number of days in the month,
- N is the mean number of daylight hours in a particular month,
- a is an empirically derived exponent which is a function of I, and is given by the formula:
  $a = 0.016*I + 0.5$.

A drawback of the method is that the calculation of PET ceases when temperature is below 0 ^oC.

Facilitating the calculation, the value of N can be taken by tables that have been constructed for latitudes ranging from 36^o to 46^o, as shown in the next table (Mimikou and Baltas, 2002):

Table 1: Mean monthly values of daylight duration N (hours) in the northern hemisphere for latitudes ranging from 36^o to 46^o

Month	Latitude φ (^{o})					
	36	**38**	**40**	**42**	**44**	**46**
Jan.	9.8	9.7	9.5	9.3	9.1	8.9
Feb.	10.6	10.5	10.4	10.3	10.2	10.1
Mar.	11.7	11.7	11.7	11.7	11.6	11.6
Apr.	12.9	13.0	13.0	13.1	13.2	13.3
May	13.9	14.0	14.2	14.4	14.5	14.7
Jun.	14.4	14.6	14.8	15.0	15.2	15.5
Jul.	14.2	14.4	14.5	14.7	14.9	15.2
Aug.	13.4	13.5	13.6	13.7	13.8	13.9
Sep.	12.2	12.2	12.3	12.3	12.3	12.3
Oct.	11.1	11.0	10.9	10.8	10.7	10.7
Nov.	10.1	9.9	9.8	9.6	9.4	9.2
Dec.	9.6	9.4	9.2	9.0	8.8	8.5

Serving the purposes of the investigation, suitable routines for the calculation of the parameters have been developed in the Microsoft Excel environment. For each meteorological station, the following calculations were carried-out:

1. Filling in of any missing information in the raw temperature timeseries, by adoption of suitable methods (linear regression)
2. Calculation of mean monthly temperature from the exported raw timeseries of the database of NDBHMI,
3. Calculation of I index from the previously calculated values of mean monthly temperature
4. Estimation of PET by application of equation (1)

The calculations were repeated for all years that make up the temperature timeseries in each station, and the estimated monthly, annual and interannual values of potential evapotranspiration were stored in tabular and graphical form.

2.2 Blaney-Criddle method

In investigating evapotranspiration, the spatial variability of surface vegetation properties is important. The Blaney-Criddle formula addresses this need by including a seasonal crop coefficient in the formula that depends on sowing date, rate of crop development, length of growing season and climatic conditions. The method was initially used for estimating consumptive use of irrigated crops in the western United States and the respective equation is applied to estimate potential evapotranspiration in agricultural fields or catchments with fairly uniform vegetation. It has the following form:

$E = 0.254 * k_c * p * (32 + 1.8 * T)$ (2)

where:

- E is monthly potential evapotranspiration (mm/month),
- T is mean monthly temperature (^oC),
- k_c is the seasonal crop coefficient
- p= ratio of mean daily daytime hours for a given month to the total daytime hours
- in the year as a percent
- n/N= ratio of actual (n) to maximum possible (N) bright sunshine hours

After a modification by Doorenbos and Pruitt (1977), the potential evapotranspiration for a particular crop acquires a more complete but also complicated form, having a high data requirement, similar to the Penman method. Therefore, it was not possible to be applied. The range of values of the seasonal crop coefficient k_c and the factor p are provided from relative tables. Land patterns were derived from the application Corine Land Cover, by which different types of land cover throughout countries of Europe are charted. Processing of the data was done with the use of Arcview GIS. The 43 categories of land cover underwent a process of homogenisation and the final table that was constructed is the following:

Table 2: Homogenisation of land cover categories

Category	**Description**	**k_c**
1	**Water bodies**	
1.1	Sea	0.45
1.2	Other water surfaces	0.80
2	**Urban**	0.30
3	**Agricultural**	
3.1	Tree plantations	0.65
3.2	Other plantations	0.75
4	**Forest**	0.5
5	**Other**	0.25

The data contained in the above table were used to estimate a weighted mean coefficient k_c for each water district, which was consequently used as an input to the Blaney-Criddle formula. The next table presents the results of this procedure:

Table 3: Weighted crop coefficients k_c for the water districts under investigation.

Water district	**Weighted k_c**	**Water district**	**Weighted k_c**
West Peloponnese	0.66	East “Sterea Ellada”	0.61
North Peloponnese	0.66	Thessaly	0.68
East Peloponnese	0.67	West Macedonia	0.65
West “Sterea Ellada”	0.61	Central Macedonia	0.69
Epirus	0.63	East Macedonia	0.66

All required calculations for the estimation of potential evapotranspiration were carried-out with the use of routines developed in Microsoft Excel.

2.3 Hargreaves method

Among existing PET models, the Hargreaves model is one of the simplest for practical use, since it requires only two easily accessible parameters, temperature and solar energy. The Hargreaves equation is expressed as follows:

$$ET= 0.0023 * (S_0/\lambda)*(T +17.8)*(T_{max}-T_{min})^{0.5} \qquad (3)$$

where:

- ET is daily potential evapotranspiration rate (mm/d),
- S_0 is the extraterrestrial solar radiation ($kJ/m^2/d$)
- T is the mean monthly temperature (^oC)
- λ is the latent heat of evaporation (kJ/kg)
- T_{max} is the monthly maximum temperature (^oC)
- T_{min} is the monthly minimum temperature (^oC)

Bibliographical resources (Mimikou and Baltas, 2002) provide S_0 as a function of season and latitude in a tabular form

3. SPATIAL INTEGRATION OF POINT ESTIMATES

Four methods have been employed for the spatial integration of the point evapotranspiration estimates. These were the Inverse Distance Weighting method (IDW), the method of Splines, the Kriging method and the Thiessen method. All the relevant work was carried-out in a GIS environment and specifically with the use of the package ArcView (ESRI). The brief description of these approaches follows.

3.1 Inverse distance weighting

This is one of the most commonly used techniques for interpolation of scatter points. Inverse distance weighting (IDW) methods are based on the assumption that the interpolating surface should be influenced more by the nearby points and less by the distant points. IDW interpolation uses a desired number of closest known neighbourhood points to find the unknown point. The known points are weighted according to their distance from the unknown point. The interpolating surface is a weighted average of the scatter points and the weight assigned to each scatter point diminishes as the distance from the interpolation point to the scatter point increases.

3.2 Method of splines

Splining is a deterministic technique to represent two-dimensional curves on three-dimensional surfaces. This method operates by passing a polynomial function through known data points in order to interpolate the unknown points. Splining may be thought of as the mathematical equivalent of fitting a long flexible ruler to a series of data points. Like its physical counterpart, the mathematical spline function is constrained at defined points (CTech. Development Corporation, 2003). Splining assumes smoothness of variation and has the advantage of creating visually appealing curves and contour lines. Some of splining's disadvantages are that no estimates of error are given and that splining may mask uncertainty present in the data. Splines are typically used for creating contour lines from dense regularly spaced data. Splining may, however, be used for interpolation of irregularly spaced data as well.

3.3 Kriging method

It is a stochastic technique similar to inverse distance weighted averaging in that it uses a linear combination of weights at known points to estimate the value at the grid nodes. Kriging is named after D.L. Krige, who used Kriging's underlying theory to estimate ore content. It incorporates a general trend and a specified number of points to weight from and adds a random noise component to the calculation to find the value of the point being interpolated. Kriging uses a variogram (a.k.a. semivariogram), which is a representation of the spatial and data differences between some or all possible "pairs" of points in the measured data set (CTech. Development Corporation, 2003). The variogram then describes the weighting factors that will be applied for the interpolation. Unlike other estimation procedures investigated, Kriging provides a measure of the error and associated confidence in the estimates.
Under the statistical theory that includes “Universal Kriging”, a single-valued, continuous, mappable property is called a "regionalised variable" and is considered to consist of two parts: a drift, or expected value, and a residual, or deviation from the drift. The drift may be modelled by a local polynomial function within a neighbourhood that is analogous to a local trend surface. If the drift is removed, the residual surface can be regarded as first-order stationary in a statistical sense. (Kansas Geological Survey, 2003)

3.4 Thiessen method

The Thiessen approach is a graphical approach, adjusting for the non-uniform location of gauging stations by determining their area of influence. The method is based on the construction of areas of influence centred on each point measurement, the so-called Thiessen polygons. The measurement for each point is then taken to be representative of the variable on its respective area of influence. The polygons are created by drawing straight lines between pairs of neighbouring sites. Then, at the mid-point along each of these lines, a second series of lines are drawn at right angles to the first. Linking the second series of lines creates the Thiessen polygons.

4. RESULTS

The Thornthwaite and Blaney-Criddle methods were applied for 10 water districts of the country (out of the total of 14), while the Hargreaves formula was applied only to the water district of western Macedonia. The results of the procedure are summarised in Table 5 and Figure 1.

Table 5: Areal estimates of PET for the investigated water districts (Thiessen method of spatial integration).

Water district	PET by Thornthwaite formula (mm)	PET by Blanney-Criddle formula (mm)
West Peloponnese	817.5	1028.3
North Peloponnese	829.9	1034.3
East Peloponnese	876.6	1085.7
West Sterea Ellada	792.2	923.0
Epirus	792.1	954.7
East Sterea Ellada	854.3	968.5
Thessaly	829.6	1050.9
West Macedonia	750.4	941.7
Central Macedonia	806.2	1045.6
East Macedonia	806.0	995.2

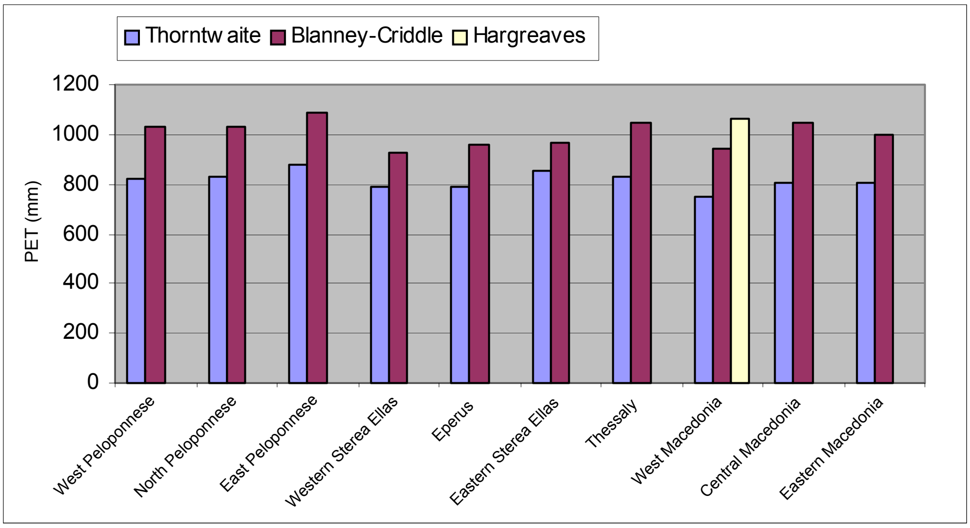

Figure 1: Summary of results: Areal PET for the investigated water districts.

Figures 2 and 3 show the maps of potential evapotranspiration for the 10 out of the 14 water districts of the country as they emerged from the application of the Thornthwaite and Blaney-Criddle formulae respectively.
For the water district of western Macedonia, the Hargreaves method in conjunction with the Thiessen method for spatial integration produced an estimate of 1066.7mm for mean interannual areal potential evapotranspiration.

Figure 2: Results of potential evapotranspiration estimated from the Thornthwaite method

Figure 3: Results of potential evapotranspiration estimated from the Blaney-Criddle method

5. CONCLUSIONS

Of the several phases in the hydrologic cycle, the one of evapotranspiration presents probably the most significant difficulties for its direct quantification. This investigation examined potential evapotranspiration and its spatial distribution for most water districts of Greece by adopting empirical approaches. The Thornthwaite and Blaney-Criddle empirical methods were chosen to estimate PET, as other more theoretical methods (e.g. Penman's formula) require several in-situ measurements of meteorological parameters, that are not readily available in the current form of the Greek network of hydrometeorological stations. These empirical methods are very popular since their only climatic data requirement is air temperature. The following conclusions were drawn regarding the investigation:

- Temperature may often not be a good indicator for evapotranspiration (radiation is by far the most important parameter), and the methods adopted in this investigation may have produced slightly erroneous results, underestimating the amplitude of seasonal fluctuations of water demand.
- The variation of PET between the three methods that were employed is explained by the different theoretical basis and the set of assumptions behind each.
- For the two main methods that were adopted (Thornthwaite equation and Blaney-Criddle formula), potential evapotranspiration appears to be slightly larger in the eastern part of the country.
- The Thornthwaite method produced smaller values (10 to 20% smaller) of potential evapotranspiration, compared to the Blaney-Criddle method. The Thornthwaite

method is known to systematically underestimate PET in more arid regions and seasons. The underestimation is particularly evident during spring, as air temperature lags behind radiation.

- The Hargreaves method (applied in the water district of western Macedonia only) tends to overestimate potential evapotranspiration by approximately 30% and 12%, compared to the potential evapotranspiration estimated by the Thornthwaite and Blaney-Criddle methods respectively.
- The density and distribution of the hydrometeorological network of the country is not satisfactory in some parts, possibly leading to areal estimates of evapotranspiration that are of questionable reliability.

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