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Comparison of different methods to estimate actual evapotranspiration and hydrologic balance

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ABSTRACT

The aim of this study was the assessment of the utilization of two methods, i.e. the Thornthwaite and the Turc equations, for the analysis of the water balance in an environmentally sensitive area. The hydrologic balance of a basin consisting in two lakes (Zazari and Cheimaditida) in northern Greece, and covering an area of 228 km^2 has been estimated. The Thornthwaite method was applied in the study area, for the calculation of the evapotranspiration factor and was compared to the results obtained by the application of the Turc method in the same area. For the development of these equations and the calculation of the evapotranspiration rates, monthly temperature and precipitation values collected from meteorological stations over a period of 30 years were used. The utilization of monthly average temperatures in the Thornthwaite equation resulted to an actual evapotranspiration rate of ET = 412.7 mm (80.23%) for p = 514.4 mm and a runoff rate of Q = 101.7 mm (19.77%). However, the Turc equation gave slightly higher values i.e. ET = 428.8 mm. Nevertheless, the application of the Turc equation, using the corrected temperature factor T_c, resulted to the calculation of an evapotranspiration value similar to the corresponding estimated by the Thornthwaite equation, indicating that the utilization of the former method could be favored, due to its simplicity over the latter one.

Keywords: Water balance; Actual evapotranspiration; Turc method; Thornthwaite equation

1. Introduction

Actual evapotranspiration (ETa) is one of the most important components in both water and energy balance equations, and its quantification is important for researchers working in hydrology, agronomy, forestry, and environmental science, including issues related to water resources management [1], planning of water-saving initiatives in irrigated areas [2], and impact of climate change on water resources [3,4].

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The ETa is an appropriate parameter for the assessment of the rational use of water resources in an area. Spatial and time ETa variations, from various land use applications (particularly from irrigated lands), are considered as efficient indications of the adequacy, reliability, and equity in water use; the knowledge of these variations is essential for the development of a sustainable water resources management plan. The evaluation of this parameter is becoming more critical, when it is related to an area characterized by a large number of water bodies, with a high environmental susceptibility.

Unfortunately, ETa estimation under actual field conditions still remains a very challenging task; the complexity associated with the estimation of ET has led to the development of various methods for the estimation of this parameter and the corresponding time fluctuations [5,6]. Several techniques have been reported for the measurement of evapotranspiration by weighting lysimeters [7], field water balance equations [8], or micrometeorological methods [9]; however, these techniques proved to be time-consuming and expensive. Nevertheless, evapotranspiration can be estimated from climatic data, linking evapotranspiration to one or more climatic variables [10]. The consistency of various equations has been assessed under a variety of climatic conditions [5,11]. Methods that have been applied for the estimation of water balance in basins or territories include the Thornthwaite and Mather equation [12], the Turc equation [13], the Coutagne [14], Penman [15], Serra [16], Cappus [17], Kessler [18], Jensen and Haise [19], Blaney and Criddle [20], and Papadakis [21]. The above methods are mainly empirical; the common issue in these methods is the calculation of certain components of the water balance based on various factors such as temperature, precipitation, humidity, etc. The methods of Thornthwaite and Turc seem to be the most appropriate; however, their application is greatly affected by the regional conditions prevailing in a particular area. In addition, the more sensitive an area and the corresponding environmental pressures, the more imperative the requirement for the application of an appropriate method for the estimation of the area water balance and the development of an efficient water resources management plan.

The objectives of this study are: (1) the estimation of the evapotranspiration rate in an environmentally sensitive hydrologic basin consisting in two lakes, by using the Turc and Thornthwaite methods; (2) the comparative evaluation of the results obtained by the two methods based on long-term climatic data; and (3) the calculation of the water balance in the particular area and the determination of the potential for the implementation of the Thornthwaite or the Turc method for the estimation of ETa. This process is becoming considerably important, especially for the target area, as in addition to valuable conclusions that may be deduced for the justification and validity of the examined methods, it is expected to contribute to the development of an appropriate water resources management plan in the area, which currently is subjected to significant environmental pressures, mainly due to industrial activities associated to the existence of thermal lignite power plants in the area.

2. Material and methods

2.1. Description of the study area

The study area includes the hydrologic basin of two lakes in Greece, Zazari, and Cheimaditida lakes. Cheimaditida lake includes a Watergate in the area of Rodona. The total surface of the target land is about 228 km^2; about 34.7 km^2 is the surface of the Cheimaditida sub-basin, while 98.4 km^2 is the surface of the lake Zazari sub-basin. The surface of the first lake is 9.5 km^2 and the corresponding surface of the latter one is 1.9 km^2, as shown in Fig. 1 [22].

This hydrologic basin is part of the greater basin of Vegoritida lake. The target basin is located on the southeastern part of Florina prefecture. The lake Cheimaditida is about 1.5 km from Anargiroi village, while Zazari lake is close to Limnochori.

The hydrologic network of the basin is consisting of a number of small length streams, which are discharged directly to the lakes or are quenching in the neighboring sediments: streams Sklithro, Fanorema, and Amintas, which is discharged to the Petron lake (Fig. 2) [23].

In the greater area, there are 11 meteorological stations; these stations were installed at various points as shown in Fig. 3 to cover the whole area, and were set into operation since 1964. The meteorological station that was used in this work for the estimation of evapotranspiration rate is the station of Limnochori, located in the center of the study area; the data from this station were used for the homogenization and normalization of the meteorological data. This area of the station has the following coordinates: latitude 21°34′N and longitude 40°38′E. Several hydro-meteorological variables, including air temperature, wind speed, relative humidity, solar radiation, vapour pressure, and evaporation, have been continuously recorded in the period from 1964 till 1998.

The study area has a climate type which differs from the typical Greek Mediterranean climatic conditions, due to the high altitude (600–1900 m) and the

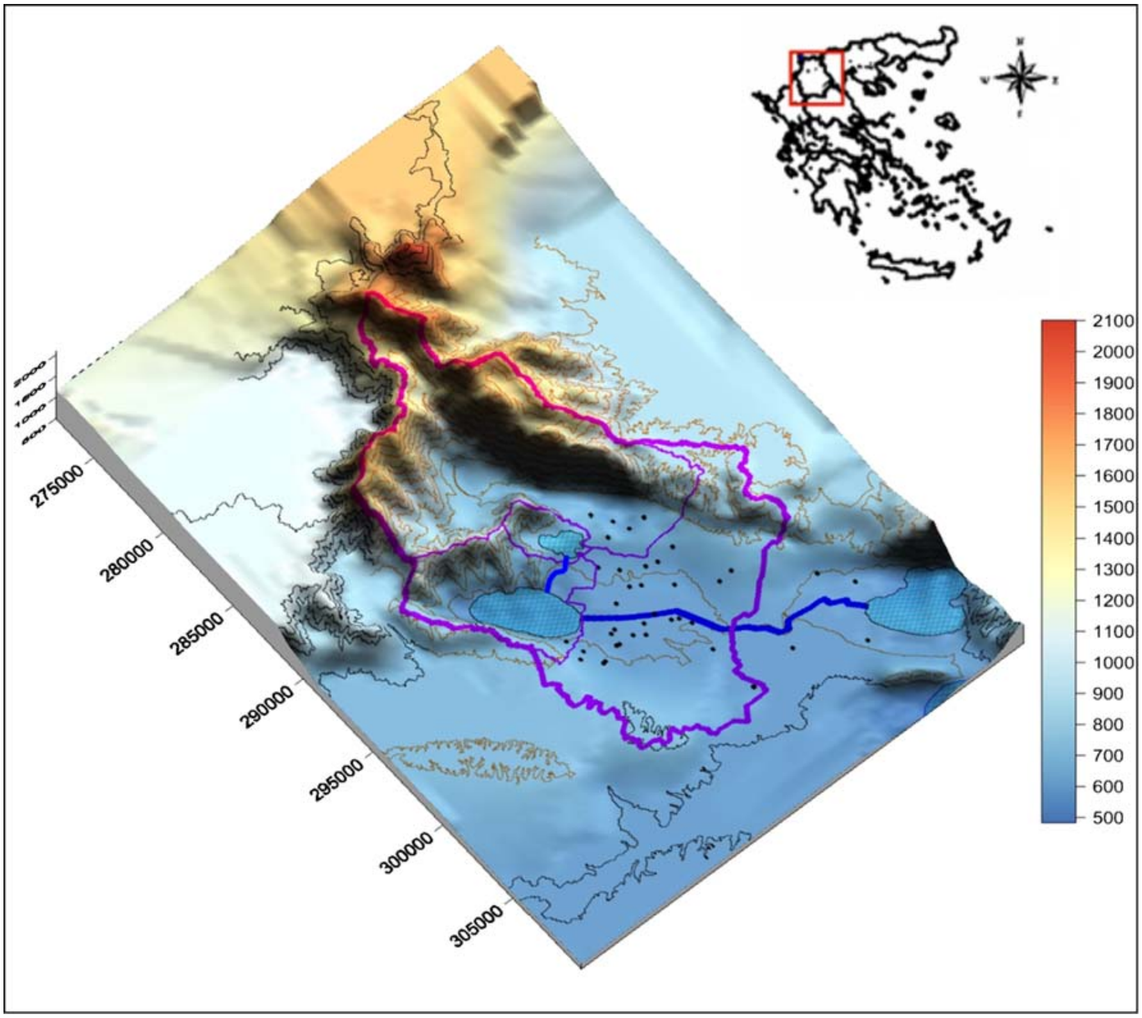

Fig. 1. 3D topographical map of the hydrological basin of lakes Zazari and Cheimaditida.

long distance from the sea side. In addition, as the study area is located in the continental mainland, and there are not any mountains in the northern side, the climatic conditions are more similar to the middle-European corresponding ones. As a result, the summer season is warm with maximum temperatures observed during July, while winter is cold with minimum temperatures during January. Spring frosts are often extended till the end of April, while the snow period starts on November and sometimes is prolonged till April.

2.1.1. Geological background

The study area belongs to the Pelagonic geotectonic zone and is located in the southeastern part of the greater hydrologic basin of Vegoritida. This zone is extended from north-northwestern to north-northeastern and starts from the borders between Greece and FYROM up to the Magnesia peninsula and the Skiathos and Skopelos islands [24]. It consists of Paleozoic and pre-Paleozoic metamorphic rocks, on which Neogene and Quaternary sediments have been developed.

The Zazari lake and the southwestern part of the Cheimaditida lake have been developed on these metamorphic rocks (gneiss, amphibolitic, and slates), which are water impermeable structures In a distance of about 2.5–3 km northeastern from the Cheimaditida lake, and close to the draining ditch, slates have been found in three wells, in depths of 419, 425, and 489 m, respectively. However, in a longer distance from the lake to the northeastern side, in the center of the basin, no similar background was found in wells with depths exceeding 500 m.

In addition to these rocks, carbonate rocks were found, below the Neogene geological formations from the Mesozoic Era in various depths in five wells in

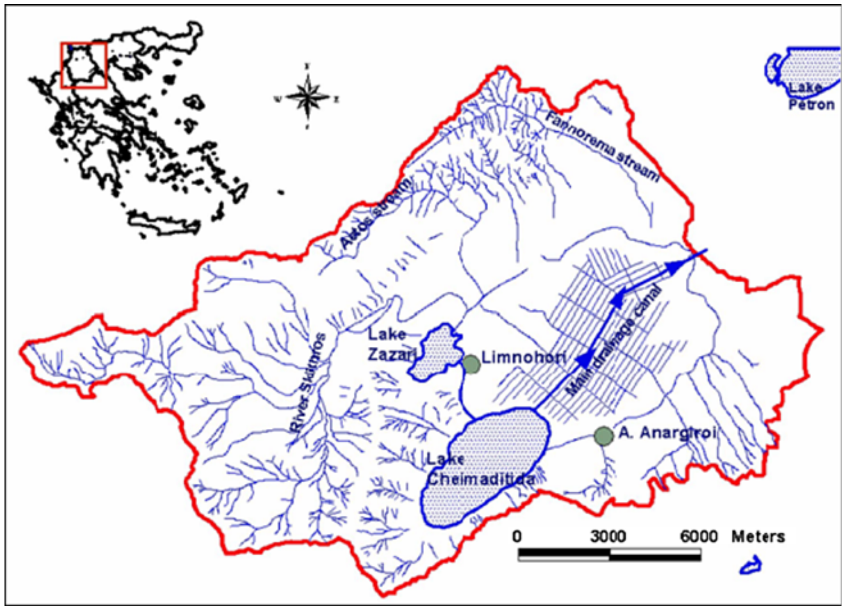

Fig. 2. Graphical representation of the hydrological basin of the lakes Zazari and Cheimaditida, in northern Greece.

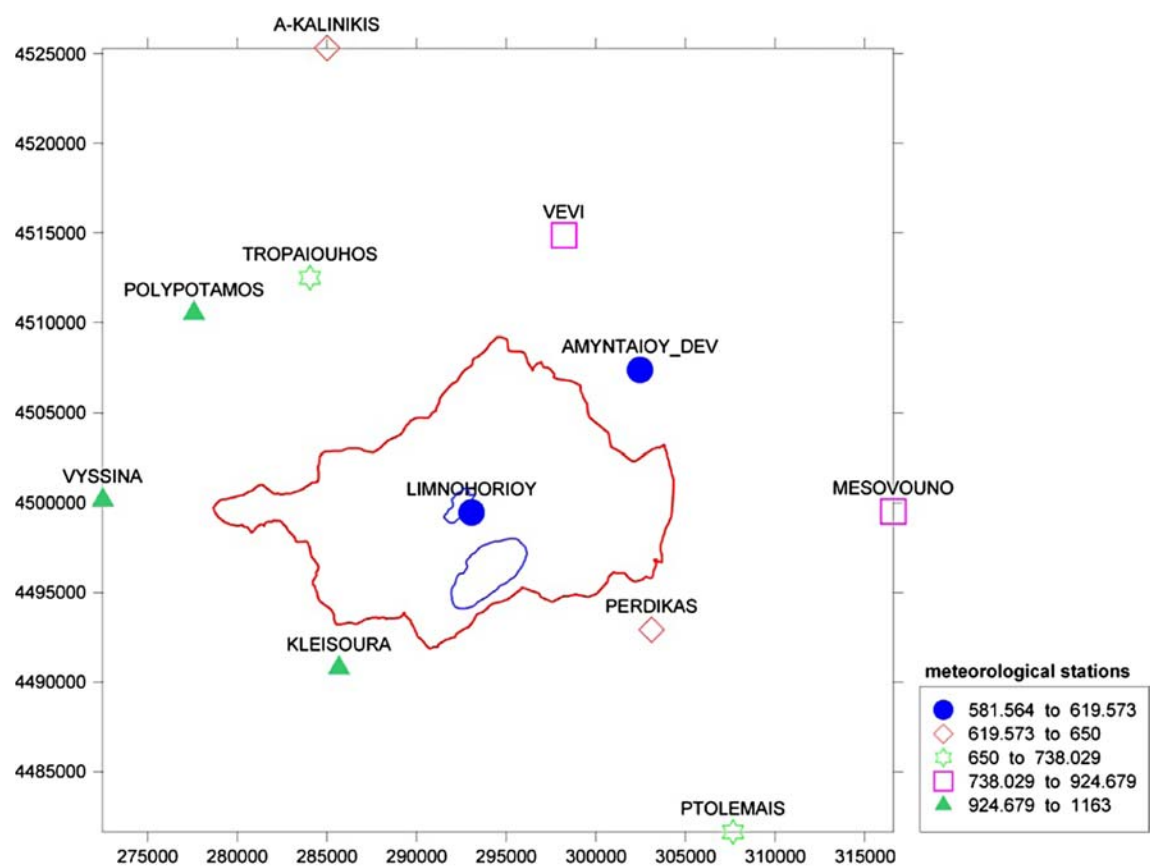

Fig. 3. Location of the meteorological stations in the study area of the hydrological basin of the two lakes.

different locations to the eastern and northeastern side of Cheimaditida lake. These rocks were found in depths ranging from 135 to 435 m. Limestone was found in two wells in depths 413 and 435 m, respectively, in a distance of 3.7 and 2.4 km northeastern from the lake. In lower depths (130–170 m), these rocks were found in an area in the eastern side from Anargiroi village in approximately 5 km from the northeastern border of the Cheimaditida lake.

Between the impermissible substrate of the metamorphic rocks and the bottom of the lakes, the Neogene sediments have been deposited, as a result of the physical weathering of the neighbouring mountainous structures.

2.2. Methods

Two methods were used for the estimation of the evapotranspiration rate in the study hydrological basin, based on the Thornthwaite and the Turc equations, respectively.

2.2.1. Thornthwaite method

Thornthwaite proposed an empirical method to estimate the potential evapotranspiration from mean temperature data. Air temperature is used in this method as an index of the energy available for evapotranspiration, assuming that the air temperature is correlated to the integrated effects of net radiation and the other parameters affecting evapotranspiration. The Thornthwaite equation is given below:

$$\mathrm{PE} = 16 \times \left(10\frac{T}{I}\right)^{a} \tag{1}$$

where PE: monthly potential evapotranspiration, T: monthly mean air temperature (℃), I: heat index for the station which is the sum of 12 monthly heat indices,

$$I = \sum_{n=1}^{n=12} i_n = \sum_{n=1}^{n=12} \left(\frac{T}{5}\right)^{1.514} \tag{2}$$

i is given by

$$i = \left(\frac{T}{5}\right)^{1.514} \tag{3}$$

and a is a cubic function of I, defined by the following equation:

$$a = 6.756\times10^{-7}\times I^3 - 7.71\times10^{-5}\times I^2 + 1.79\times10^{-2}\times I + 0.49239 \tag{4}$$

Both a and I can be found from tables mentioned in the work of Thornthwaite and Mather [25].

This method for the calculation of the monthly water balance was revised and summarized by Thornthwaite and Mather [25] in order to be used over a wide range of soils and vegetations. For the determination of the water balance at a specific site, it is necessary to collect data on the following parameters:

(1) latitude;
(2) mean monthly air temperature;
(3) mean monthly precipitation;
(4) necessary conversion and computation tables; and
(5) information on the water-holding capacity of the certain depth of the soil for which the balance is going to be computed.

2.2.2. Turc method

Turc proposed the following empirical method to estimate the ETa from mean annual temperature data:

$$E = \frac{P}{\sqrt{0.9 + \frac{P^2}{L^2}}} \tag{5}$$

where E: annual actual evapotranspiration, mm, P: annual rainfall, mm, T: mean annual temperature, ℃, and L: thermal indicator, defined by the following equation:

$$L = 300 + 25T + 0.05 \times T^3 \tag{6}$$

3. Results and discussion

3.1. Estimation of the potential evapotranspiration rate (PET) by the Thornthwaite equation

The application of the modified Thornthwaite equation [26] in the study area, using the average values of temperatures, resulted to the data given in Table 1. In this table, the following features are included: the average monthly temperatures are presented in row 1, as calculated by the daily values over a period of 30 years. The monthly heat index i estimated by Eq. (3) is shown in row 2, while the annual heat factor I calculated by Eq. (2) is given in row 3. The average annual potential transpiration rate PET estimated by Eq. (1) is presented in row 4, while the correction factor for the certain area latitude n is shown in row 5 (latitude = 40°). The normalized evapotranspiration PETn = PET × n is shown in row 6, the average monthly precipitates in row 7, and the required water amounts Uw, calculated as (PETn-P) in row 8. The available water reserves were assumed

Table 1
Water balance data for the study hydrologic basin, estimated by the Thornthwaite equation and the mean monthly temperatures

Water balance

Temperatures in C. water balance terms in mm

	Month	J	F	M	A	M	J	J	A	S	O	N	D	Year
1	*T*	2.60	3.80	6.60	11.30	15.90	19.80	22.00	21.60	18.10	13.50	7.90	4.50	12.30
2	*i*	0.37	0.66	1.52	3.44	5.76	8.03	9.42	9.16	7.01	4.50	2.00	0.85	
3	*I*													52.74
4	PET	6.3	10.4	21.5	43.8	68.7	91.8	105.6	103.0	81.6	55.4	27.3	13.0	628.4
5	*n*	0.84	0.83	1.03	1.11	1.24	1.25	1.27	1.18	1.04	0.96	0.83	0.83	
6	PET_n	5.3	8.6	22.2	48.6	85.2	114.8	134.1	121.6	84.8	53.2	22.6	10.8	711.8
7	*P*	37.0	38.4	44.4	41.3	54.5	22.1	21.8	29.5	24.4	51.5	88.4	61.1	514.4
8	*U*	0.0	0.0	0.0	7.3	30.7	92.7	112.3	92.1	60.4	1.7	0.0	0.0	
9	*Wv*	31.7	29.8	22.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	65.8	50.3	
10	*APWL*	0.0	0.0	0.0	−7.3	−38.0	−130.8	−243.0	−335.1	−395.5	−397.2	0.0	0.0	
11	St	100.0	100.0	100.0	93.0	68.4	27.0	8.8	3.5	1.9	1.9	67.6	100.0	
12	*Δ*St	0.0	0.0	0.0	−7.0	−24.6	−41.3	−18.2	−5.3	−1.6	0.0	65.8	32.4	
13	ETa	5.3	8.6	22.2	48.3	79.1	63.4	40.0	34.8	26.0	51.5	22.6	10.8	412.7
14	Dw	0.0	0.0	0.0	0.3	6.1	51.4	94.0	86.8	58.9	1.6	0.0	0.0	
15	*Q*	31.7	29.8	22.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	18.0	101.7

Note: where: *T* = mean monthly temperature;
i = monthly heat index;
I = heat index;PET = potential evapotranspiration;
n = amplitude index, 40°;
PETn = normalized potential evapotranspiration;
P = monthly precipitation;
Uw = required or lacking amount of Water;
Ew = excess water for vegetation;
APWL = water lost from ground surface due to moisture reduction;
St = soil moisture;
ΔSt = change in soil moisture;
ETa = actual evapotranspiration;
Dw = water deficiency; and*Q* = runoff water.

to correspond to 100 mm of water column. The water amount available for vegetation, calculated as (P-PETn) is given in row 9. The water lost from soil surface due to moisture reduction, APWL, is presented in row 10. The APWL is negligible when precipitates are higher than PET, otherwise it is estimated by adding the APWL value from the previous month to the current month value of the difference (P-PETn). Ground moisture is presented in row 11, while in row 12, ΔSt corresponds to the groundwater monthly change. The ETa is calculated in row 13, the water deficiency Dw = PETn − ETa in row 14 while values in row 15 represent the water runoff Q, and are calculated using the following assumption: $Q = \text{Ew} - \Delta\text{St}$ when Ew > 0, while $Q = 0$ when Ew = 0. When water moisture is higher than soil moisture withdrawal rate, then excess water is available for runoff.

3.2. Estimation of the water balance in the study hydrological basin

The surface of the study area, as mentioned in Section 2.1, is $F = 228\ \text{Km}^2$; the annual precipitated water volume is given by the following equation:

$$V = P * F \tag{7}$$

where P is the average annual precipitation rate; for the study area, as shown in Table 1, the annual precipitates calculated to 514.4 mm. Thus, the annual precipitates over the whole basin estimated to $V = 117.28 \times 10^6\ \text{m}^3$.

About 412.7 mm of water column corresponded to the annual evapotranspiration indicating that the real annual evapotranspiration in the study area is:

$$\text{V1} = \text{ETa} \times F = 94.09 \times 10^6\ \text{m}^3$$

As a result, from a total of $117.28 \times 10^6\ \text{m}^3$ precipitated in the area, about $94.09 \times 10^6\ \text{m}^3$ are evapotranspirated through the plants, while the residual amount, $Q = \text{P} - \text{ETa}$, i.e. $23.19 \times 10^6\ \text{m}^3$ corresponds to the ground infiltration (I) and the runoff (R), representing 101.7 mm of water column. Consequently, the hydrologic balance equation of the area is given by the following Eq. (8):

$$P1 = \text{ET} + I + R = \text{ET} + Q \tag{8}$$

Estimation of the real evapotranspiration may take place by the application of the modified Thornthwaite–Mather method in the corresponding hydrological basin. According to this method, the potential evapotranspiration should be calculated initially followed by the estimation of the real effective evapotranspiration. In order to justify the validity of the Thornthwaite–Mather method, the results that have been calculated by this method will be compared to the corresponding results deduced by the application of the Turc method, given by Eq. (9). In general, the models that have been proposed for the estimation of the real evapotranspiration are based on the precipitation rate P, while the models for potential evapotranspiration are taking into account the temperature factor.

3.3. Utilization of the Turc method

The application of the Turc method in the study area, with the following values for $p = 514.4$ mm and for $T = 12.3\,^{\circ}\text{C}$, resulted to the estimation of an annual evapotranspiration rate of ET = 428.8 mm. Review of worldwide hydrological data from a number of 254 basins showed that the reported results were similar to the results estimated in this study by using the Turc equation. This model is best applied at precipitates higher than 700 mm. In addition, it has been suggested that the temperature factor T should be replaced by the corrected temperature parameter (T_c), which takes into account the annual distribution of precipitation over the course of air temperature, as given in Eq. (9).

$$T_c = \frac{P_1 \times T_1 + P_2 \times T_2 \ldots + P_{12} \times T_{12}}{P_1 + P_2 + \ldots P_{12}} \tag{9}$$

The results deduced by the application of the Turc equation in the study area, using the corrected temperature factor are presented in Table 2, while a comparison of the results obtained by the application of the Turc (both by T and corrected T) and the Thornthwaite equations are shown in Table 3.

As shown in Table 3, the values calculated by the two methods are similar, with the Turc equation resulting in slightly higher values. In addition, evapotranspiration rates were higher that runoff rates, while as presented in Fig. 4, the hydrological basin is mainly replenished by inflow water corresponding to a positive water balance in the period between October and April, while in the period between April and middle October, there is a negative water balance corresponding to a Dw; during this period, soil moisture is utilized for evaporation.

Table 2
The results of the evapotranspiration rate in the study hydrological basin, by the application of the Turc equation using the corrected temperature factor

	J	F	M	A	M	J	J	A	S	O	N	D	Year
P	37.0	38.4	44.4	41.3	54.5	22.1	21.8	29.5	24.4	51.5	88.4	61.1	514.4
T	2.6	3.8	6.6	11.3	15.9	19.8	22.0	21.6	18.1	13.5	7.9	4.5	12.3
$P*T$	96.2	145.9	293.0	466.7	866.6	437.6	479.6	637.2	441.6	695.3	698.4	275.0	10.8
T_c	10.8												
L	631.1												
Etavg	411.3												

Table 3
The values of the water balance components in the study hydrological basin, as estimated by the Turc and Thornthwaite methods; both T and corrected T were used in the Turc equation

Method		P	E^*	Q
1a. Turc using T	%	100	83.36	16.64
	mm	514.4	428.8	85.6
	$10^6\,m^3$	117.28	97.76	19.52
1b. Turc using T_c	%	100	79.96	20.04
	mm	514.4	411.3	103.1
	$10^6\,m^3$	117.28	93.77	23.51
2. Thornthwaite and Mather (1955)	%	100	80.23	19.77
	mm	514.4	412.7	101.7
	$10^6\,m^3$	117.28	94.09	23.19

3.4. Hydrological results in similar basins in Greece

One of the study objectives was the evaluation of the results from the particular hydrological basin and their assessment against the corresponding results from other basins in the Hellenic region. However, limited information on similar basins is available: in an early study, the water balance of Xyniada and Sofaditi basins was calculated for a nine-year period (from October 1972 to September 1981) and was based on direct and reliable field measurements. It was found that for the former basin, precipitation (P) was 522.9 mm, evapotranspiration (E) was 366.7 mm (70.1%), and runoff (Q) was 156.2 mm (29.9%). For the latter basin, the corresponding values were: $p = 790.7$ mm, $E = 466$ mm (56.4%), and $Q = 323.9$ mm (43.6%). Turc's method, applied by using the normal temperature T, resulted to a considerable overestimation of the ETa (by 20 and 18%, respectively, for both basins), whereas by using the corrected value Tc, the Turc's method resulted to a lower overestimation of E values (13.8 and 4.5%, respectively). Therefore, for both basins, Turc's method resulted to excess values of evapotranspiration especially under lower precipitation; nevertheless, the utilization of the corrected temperature factor T_c resulted to more reliable data [27]. Another area that has been well characterized is the Vromolimnes basin in Central Macedonia, with an area of 169 km^2, average slope $i = 25\%$, vegetative cover $u =$ moderate, lithological composition corresponding to a mixture of metamorphic rocks 65% and alluvium 35%, average annual air temperature $T = 13^\circ$ C, and an annual precipitation value (P) of 601.1 mm for the years 1980–1982. Soulios and Dimopoulos [28] found the following water balance values for this area: $Q = 17\%$ and $E = 83\%$. In central and northern Greece, three karstic regions with $T = 10$–14.5°C, $p = 623.8$–764 mm, and a moderate vegetative cover gave a runoff coefficient of 45–52% [29]. These regions are mainly karstic and with a great deviation from average lithological composition of the Hellenic area. The implementation of the Turc and Thornthwaite forms in the water balance equations in two areas, i.e. in Xyniada and Sofaditi basins, gave the results presented in Table 4 [27].

The results obtained for the two regions are similar to the results deduced by the current work: similar

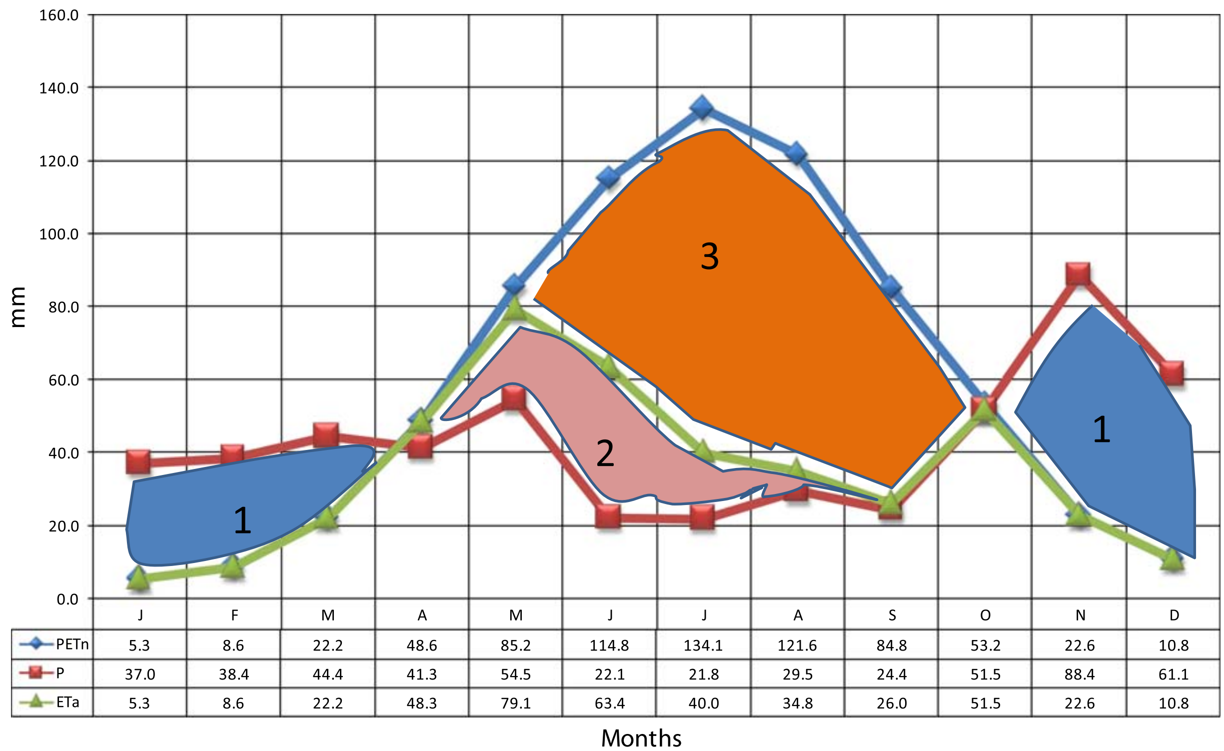

Fig. 4. Water balance by Thornthwaite–Mather equation: (1) replenishment of soil water + infiltration + runoff; (2) soil moisture utilized for evaporation; and (3) real water demand.

Table 4
The water balance results by the implementation of Turc and Thornthwaite equations for the basins of Xyniada and Sofaditi basins [27]

Method	Xyniada basin $p = 522.9$ mm		Sofaditi basin $p = 790.7$ mm	
	E%	*Q%*	*E%*	*Q%*
Thornthwaite	75.1	25.9	54.4	45.6
Turc	84.3	15.7	69.7	30.3
Turc				
Tc	79.8		61.6	38.4

values were estimated for both equations, although the Turc method gave slightly higher results. In addition, evapotranspiration rates were higher than runoff values, similar to the results found for Zazari and Cheimaditida lakes.

4. Conclusions

The aim of this work was the estimation of the real evapotranspiration amount in an environmentally sensitive basin consisting in two lakes, in northern Greece, by the use of the modified Thornthwaite method. The Thornthwaite equation was applied for the calculation of the potential evapotranspiration rate, based on the average monthly ETa, as deduced by the analysis of meteorological data over a long-term period, and taking into account the average monthly precipitation rate and the corresponding water reserves required for plant development. The excess or deficient water may be calculated for each month and can be used in the water balance equation.

For the particular basin, the Thornthwaite equation, for mean monthly temperatures, gave an ETa rate of ET = 412.7 mm (80.23%) for $p = 514.4$ mm and a runoff rate of $Q = 101.7$ mm (19.77%). However, the Turc equation gave lightly higher results, i.e. ET = 428.8 mm (83.36%).

By comparison of the Turc and the Thornthwaite methods, it can be concluded that although the Turc equation is simpler than the latter for the estimation of the real evapotranspiration, the calculated values are slightly higher than the Thornthwaite ones. In general, results estimated for the Greek basins are higher, but for the particular basin both models gave similar values. It was found that by the application of the Turc equation using the corrected temperature, an Evapotranspiration value is calculated which is similar to the corresponding estimated by the Thornthwaite equation.

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