Chapter

Effect of the Evapotranspiration of Thornthwaite and of Penman-Monteith in the Estimation of Monthly Streamflows Based on a Monthly Water Balance Model

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Abstract

The river discharge monitoring networks are generally sparser and more recent than those of other hydrological variables, like rainfall or temperature. Furthermore, most of the streamflow series show long periods without records and several gaps, thereby limiting their use. Hydrological modeling provides a tool to overcome the poor quality of the streamflow data. However, its applicability to fill in the gaps or increase the time spans of the existing series and also to estimate streamflows at ungauged catchments depends on the simplicity and on the few data requirements of the approach selected, which makes the water balance models suitable choices. In the previous scope, the role of evapotranspiration in a water balance model was investigated for Portugal based on two approaches: a more complex with more data requirements, the Penman-Monteith method, and a very simple one only based on temperature data, the Thornthwaite method. The results showed that the monthly streamflows estimated based on any of the previous evapotranspiration models are almost the same. In fact, when the differences between the two models are higher, the surface runoff process is no longer controlled by the evapotranspiration but instead by the absence of rainfall and by the dryness of the soil.

Keywords: water balance model, evapotranspiration, Penman-Monteith, Thornthwaite, data scarcity

1. Introduction

The scarcity and the deficient quality of the discharge data are common problems in hydrological modeling. In fact, most of the river basins across the world are ungauged or poorly gauged, without in situ monitoring for the most relevant hydroclimatic variables [1], with emphasis on river discharges. Such whole spectra of cases are embraced now under the term "ungauged basins" meaning catchments where meteorological data or river flow, or both, is not measured [2]. The prediction in ungauged basins (PUB) is so relevant that in 2003, the International

Association of Hydrological Sciences (IAHS) launched an initiative for 10 years aiming at contributing to shift the scientific culture of hydrology toward improved scientific understanding of hydrological processes so that data scarcity or unavailability could be overcome [3].

As the majority of worldwide basins [3], the Portuguese ones are also ungauged or poorly gauged. In fact, in Portugal, the systematic measurement of its river discharges started much later than that of other hydrometeorological variables resulting in much sparser monitoring networks with much more recent records. Additionally, most of the discharge data series thus acquired have recurrent gaps, either sporadic or for long periods, thereby limiting their use for both scientific hydrological studies and design purposes. These circumstances bring forward the need to apply hydrological models aiming not only at filling in the gaps in the records or at increasing their time spans but also at estimating discharges at ungauged catchments. Therefore, hydrological modeling can be looked as a tool to solve the problem of the lack of river discharge data or of the poor quality of the existing data.

However, almost regardless of the purpose of a hydrological model, its applicability depends on its simplicity and on the compatibility between its data requirements and the available information.

The hydrological models may have different degrees of complexity [4]. One of the disadvantages of using more complex hydrological models is that they require more data and more considerable effort in parameterization.

Greater complexity, however, does not mean that a model is better. According to Jakeman et al. [5], some simple models have performed more complex (or better than) alternatives in some cases. Over-parameterization and a lack of appropriate data for parameterization are a concern with complex models [6]. Fewer parameters that only treat the fundamental processes—a parsimonious approach to modeling—could sometimes be a better conceptualization of reality [7].

As a guiding principle, a relatively simple model is likely to be required if there are limited data. The simplest model that can be usefully applied is one that captures only those factors that are critical to the processes under study [8]. This was also stressed by Hillel [9], who stated the following principles of a model development:

- Parsimony—the model should not be more complex than the required data and should include the smallest possible number of parameter with values to be computed from the data.

- Modesty—a model should not intend to do "too much"; there is no such thing as "the model".

- Precision—a model should not intend to describe a phenomenon with precision higher than the capacity to measure it.

- Verifiability—a model must be verifiable, and it is always necessary to know its limits of validity.

The previous constraints make the water balance approach most suitable for many hydrological purposes, including those related to the improvement of the quality/length of the discharge series.

The first water balance model based exclusively on rainfall and temperature was developed in the 1940s by Thornthwaite [10] and later revised by Thornthwaite and Mather [11]. They proposed two different conceptual models based on two parameters: soil moisture capacity and water excess above the maximum soil moisture storage capacity. These models proved to be able to estimate monthly runoff [12] and provided the basis of many other two-parameter hydrological models [13, 14]. Several studies have shown that many models produce similar results to those simpler previous ones, e.g., [15–18]. The more recent water balance model of Temez model [19] also stands out among the available simplest models.

Although the Thornthwaite-Mather model is quite old, its recurrent use over time for different water management issues in different hydrological environments and the fact that many recent studies continue to adopt such approaches demonstrate its current effectiveness, e.g., [20–23].

As for the second one, it has been widely used in Spanish catchments [24]. However, both methods make use of potential evapotranspiration evaluation, which requires records of climatologic variables that are not usually readily available, except for rainfall and temperature.

In this context, the present study aims at understanding the role of different procedures to compute the evapotranspiration in the estimates of monthly streamflows obtained via the Thornthwaite-Mather monthly water balance model. The two models for the evapotranspiration were the Thornthwaite and the Penman-Monteith models. The former is recognizably simple since it only makes use of average monthly temperatures. Conversely, the latter requires records of several climatologic variables, which, in practical terms, makes it much more restrictive. The validity of the results obtained is restricted to Mainland Portugal, which means that there is an opportunity for additional research aiming at expanding the analysis and its conclusions to other hydrological environments.

2. The potential evapotranspiration: the water balance model

Potential evapotranspiration (EVP) is the process of water transfer from the soil to the atmosphere, either directly or through the plants when the water required for such process is fully available. Potential and actual evapotranspiration are very rarely measured due to the complex, expensive, and hard methodology required (e.g., percolation gauge, weighing lysimeter). Several methods and models are available for indirect evaluation, such as temperature-based methods [10, 25, 26] and radiation-based methods [27] or combined methods, as the well-known Penman-Monteith method [28].

According to Thornthwaite [10], the EVP (mm/month) for 1 month with N_d days is given by Eq. (1):

$$\mathrm{EVP} = \left[16 \times \left(10\,\frac{\mathrm{Tmed}}{\mathrm{I}}\right)^{\alpha}\right] \times \left[\frac{\mathrm{N}/12 \times \mathrm{N_d}}{30}\right] \tag{1}$$

where Tmed is the average air temperature (°C) in that month; I is an annual heat index which depends on the monthly heat indexes which, in turn, are function of the average air temperatures along the several months of the year, each with N_d number of days; α is an exponent which also depends on I; and N/12 is the astronomical day expressed in 12 h units of a 30-day month at the latitude where EVP is to be calculated.

The Penman-Monteith method yields to the potential evapotranspiration for a soil wholly covered by a reference culture (grass in active growth, with uniform height, and free of water supply limitations) [29], and, for this reason, this evapotranspiration is frequently called reference evapotranspiration, EV0. The calculation of EV0 (mm/day) for a given place can use Eq. (2):

$$EV0 = \frac{0.408\Delta(R_n - g) + \gamma \frac{900}{Tmed+273} v_2(e_a - e_d)}{\Delta + \gamma(1 + 0.34U_2)} \quad (2)$$

where Tmed is the average air temperature (°C), Δ is the slope of the saturation vapor pressure temperature relationship (k Pa°C^{-1}), R_n is the net solar radiation (MJ m^{-2} d^{-1}), g is the soil heat flux (MJ m^{-2} d^{-1}), γ is the psychrometric constant (k Pa°C^{-1}), v_2 is the mean wind velocity 2 m above the ground (ms^{-1}), e_a is the vapor saturation tension at temperature T (kPa), and e_d is the actual vapor tension (kPa). The calculation of some of the previous variables, besides its complexity, may also require the average maximum and average minimum air temperatures, the average air relative humidity, and the global solar radiation.

Thornthwaite method seems to underestimate the potential evapotranspiration in Mainland Portugal [30, 31], while the Penman-Monteith method tends to overestimate it [29]. Its results are, however, more satisfactory in a large number of different climatic, timescale, and location constraints [29].

The Thornthwaite-Mather water balance model applies the mass equation along time to an element of the terrestrial phase of the hydrologic cycle by calculating the water fluxes "entering" that element, those "leaving" it, and the variations in the water storage within that same element [10, 32–34] according to

$$P = S + EVA + \Delta S \quad (3)$$

where, for a given time interval, P is the rainfall, S is the water excess or superavit, EVA is the actual evapotranspiration, and ΔS is the water storage variation (all variables expressed in the same units).

The previous water balance model does not consider the heterogeneity of the watershed, the deep infiltration, and the complexity of the water movements (either on the surface or in the ground). In addition, it does not consider that surface runoff occurs whenever the rainfall intensity exceeds the infiltration rate. Despite these simplifications, it may be considered that the water excess or superavit, S, represents the upper limit of the surface runoff.

Within these conditions, the water balance model can be used to estimate the river discharges. In order to do so and after assigning to the soil a maximum useable water storage capacity (Smax), the model assumes that, as long as there is water availability (either storage in the ground or from the rainfall), the actual evapotranspiration rate is equal to the potential evapotranspiration; otherwise, it will occur at a lower rate. Furthermore, it also assumes that there is no onset of surface runoff if the capacity to store water in the soil is not filled up, even if the rainfall intensity exceeds the infiltration rate. The amount of water in the soil in the months where rainfall is lower than evapotranspiration can be calculated by Mendonça [35]:

$$AS_i = AS_{i-1} e^{L_i/Smax} \quad (4)$$

where AS (mm) represents the water in the soil in month identified by the index, Smax is maximum useable water storage capacity, and L_i (mm) is the water potential loss (i.e., the difference between the rainfall and the potential evapotranspiration) accumulated since the onset of the dry period up to month i.

3. Case studies and data

The precipitation regime in Portugal is highly irregular both in space and in time and, in this last case, either within the year or among the years [36, 37]. On average, around 70 (in the north) to 85% (in the south) of the annual precipitation occurs in the wet semester—from October to March.

The seasonal variability of the precipitation is due to the characteristics of the general circulation of the atmosphere and to regional climate factors, related to Portugal's geographic location, in the south-westerly extreme of the Iberian Peninsula (between 37° and 42°N and 6.5° and 9.5°W). The North Atlantic Oscillation (NAO) and other teleconnection indexes at the synoptic and smaller scales explain the interannual variability [38]. In terms of spatial variability, the mean annual precipitation varies from more than 2800 mm, in the northwestern region, to less than 400 mm, in the southern region, following a complex spatial pattern (N–S/E–W), in close connection with the relief, far beyond the most determinant factor of the precipitation spatial pattern.

Figure 1 shows the schematic location of the 16 climatological stations used in the study over a mean annual flow depth map (H in mm/year). The figure shows that the southern and the more north-eastern regions are characterized by water scarcity (rarely exceeding in average 150–200 mm/year) and that only in the center/north western region there is some surface water availability. The mean annual values of the precipitation and of the surface runoff over the country are approximately 960 and 385 mm, respectively.

The climatological stations were selected aiming at representing the different prevailing hydrological regimes in Portugal and especially at ensuring a common period with all the records required by the application of the Penman-Monteith, which in Portugal is not easy to get. The records at the previous stations were obtained from the Portuguese Institute for the Ocean and Atmosphere (IPMA), which has high data quality standards and is one of the main sources of Portuguese hydrological and hydrometeorological and also from the database AGRIBASE from the Instituto Superior de Agronomia (ISA), the School of Agriculture of the Lisbon University. Although the periods for which it was possible to obtain the required data are not very recent, this has no influence on the purpose of the study.

Some general characteristics of the previous stations are presented in **Table 1** along with the mean monthly values of the following variables, computed based on

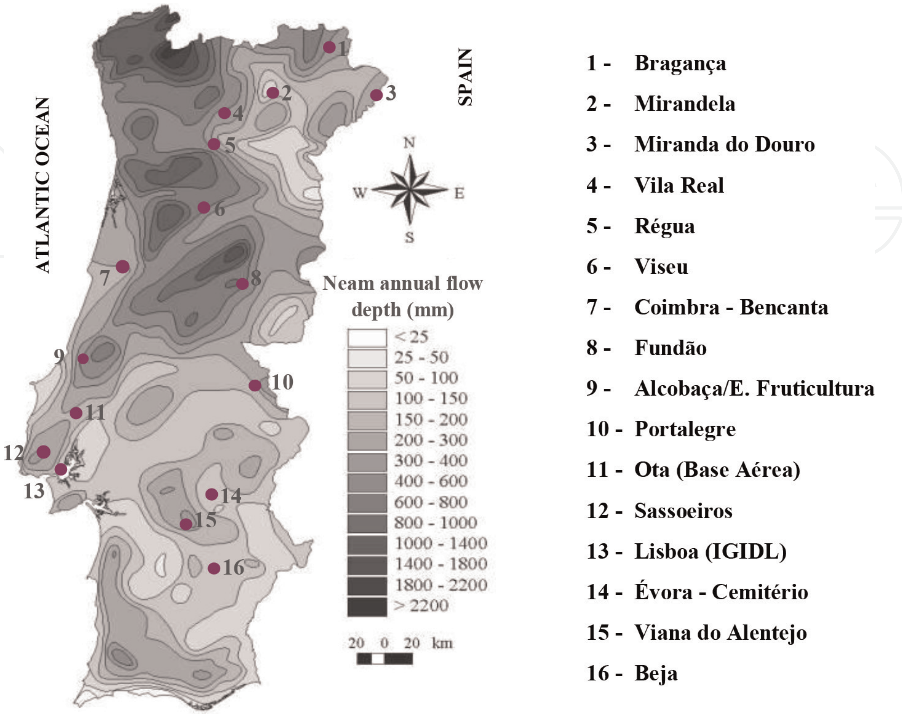

Figure 1.
*Location of the climatological stations of **Table 1**.*

Climatologic station	Period with records	Location		Altitude	Mean monthly values						
		Lat	Long	(m)	P (mm)	Tmed (°)	Tmax (°)	Tmin (°)	HR (%)	I (h)	v (m/s)
Bragança (03Q/01)	1963/64 - 1987/88	41° 48'	6° 44'	690	61.86	12.06	17.37	6.62	79.69	213.7	10.05
Mirandela (04N/02)	1959/60 - 1980/81	41° 31'	7° 12'	250	44.33	14.12	20.36	7.91	72.66	210.1	7.14
Miranda do Douro (05T/01)	1956/57 - 1965/66	41° 30'	6° 17'	693	45.94	12.36	17.68	7.15	72.23	219.8	13.86
Vila Real (06K/01)	1959/60 - 1987/88	41° 19'	7° 44'	481	99.27	13.30	18.55	8.10	82.86	195.9	7.05
Régua (07K/01)	1959/60 - 1987/88	41° 10'	7° 48'	65	78.95	15.43	21.69	9.20	77.52	186.9	5.18
Viseu (10J/01)	1961/62 - 1975/76	40° 40'	7° 54'	443	97.64	13.04	19.12	7.06	78.32	215.6	4.87
Coimbra - Bencanta (12G/06)	1959/60 - 1987/88	40° 13'	8° 27'	27	86.15	15.26	20.72	9.72	79.94	192.8	4.93
Fundão (13L/01)	1957/58 - 1963/64	40° 08'	7° 30'	495	93.81	14.19	19.65	8.75	65.90	231.6	8.80
Alcobaça/E. Fruticultura (16D/06)	1960/61 - 1976/77	39° 031'	8° 58'	38	80.64	14.91	19.72	9.37	81.86	205.8	8.17
Portalegre (18M/01)	1959/60 - 1987/88	39° 17'	7° 25'	597	75.75	15.03	19.49	10.54	72.53	223.6	14.06
Ota (Base Aérea) (19D/01)	1976/77 - 1983/84	39° 07'	8° 59'	40	56.49	16.22	21.26	11.18	78.29	216.7	10.61
Sassoeiros (21B/03)	1958/59 - 1967/68	38° 42'	9° 19'	50	59.29	15.95	20.17	11.68	77.14	214.4	13.55
Lisboa (IGIDL) (21C/06)	1958/59 - 1987/88	38° 43'	9° 09'	77	63.74	16.72	20.77	12.73	75.40	233.8	13.53
Évora - Cemitério (22J/02)	1956/57 - 1987/88	38° 34'	7° 55'	265	54.38	15.66	20.43	10.83	80.70	232.9	15.81
Viana do Alentejo (23I/02)	1958/59 - 1984/85	38° 20'	8° 03'	202	55.04	16.00	22.36	9.63	76.39	232.6	8.76
Beja (25J/02)	1958/59 - 1987/88	38° 01'	7° 52'	246	49.22	16.09	22.16	10.05	85.00	229.0	15.23

Table 1.
Climatological stations. General features and mean monthly values of precipitation, P; mean, average maximum and average minimum air temperature, Tmed, Tmax and Tmin, respectively; air relative humidity, HR; number of sunny hours, I; and wind velocity 2 m above the ground, v.

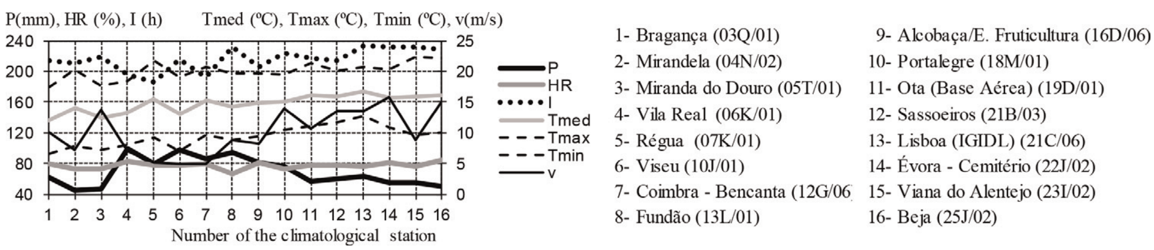

Figure 2.
Mean monthly values of P, Tmed, Tmax, Tmin, HR, I, and v, according to ***Table 1****.*

the data provided: precipitation, P; mean, average maximum and average minimum air temperatures, Tmed, Tmax and Tmin, respectively; air relative humidity, HR; number of sunshine hours, I; and wind velocity, v. In **Figure 2**, the corresponding mean monthly values are represented. The recording periods of **Table 1** refer to hydrological years, which in Portugal start on October 1.

Figure 2 shows that from the north to the south of Mainland Portugal, the precipitation decreases and the temperature and the sunshine hours increase.

4. Results

Based on the records of **Table 1**, the potential evapotranspirations of Thornthwaite (EVP) and Penman-Monteith (EV0) were computed, as well as the surface flows that they predict according to the Thornthwaite-Mather water balance model—Eqs. (3) and (4).

In **Figure 3**, the Thornthwaite (EVP) and Penman-Monteith (EV0) monthly potential evapotranspirations are compared for each of the 16 climatologic stations. Each diagram contains the representation of the straight line from the linear regression analysis between EVP and EV0, its equation, and the respective correlation coefficient. There is also a second dashed straight line representing the equality between the two evapotranspirations under consideration. The scale of the axes is always the same in order to allow the comparison between those evapotranspirations and among the results from the different climatological stations. **Figure 3** clearly highlights two relevant conclusions:

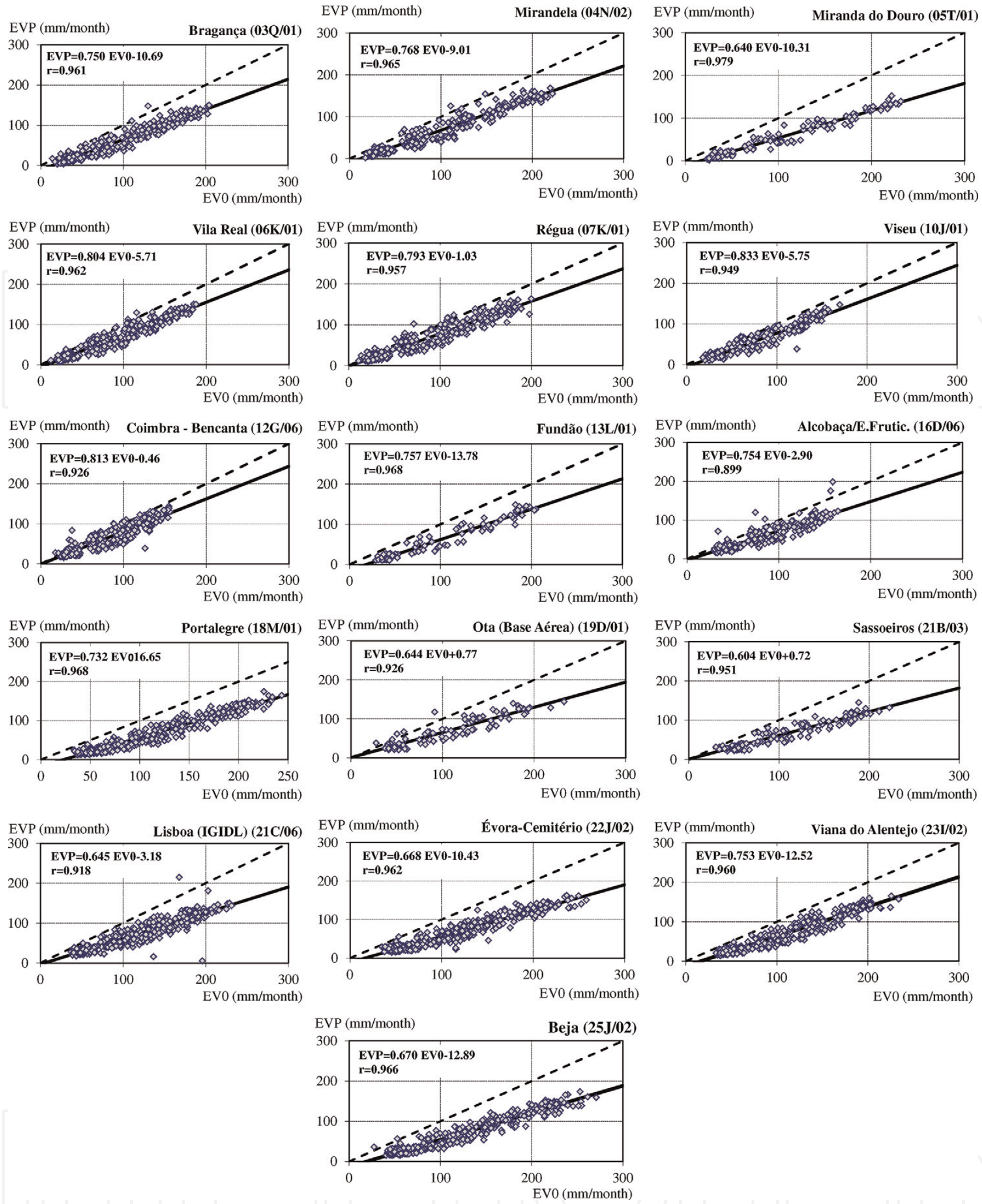

Figure 3.
Monthly potential evapotranspiration of Thornthwaite, EVP, and of Penman-Monteith, EV0. Linear regression line (continuous line), equation, and correlation coefficient, r. Line representing the equality between monthly EVP and EV0 (dashed line).

i. The values of the potential evapotranspiration of Thornthwaite (EVP) are systematically lower than those of the evapotranspiration of Penman-Monteith (EV0), thus confirming the previous knowledge for Portugal [29]; the differences between those values increase as the evapotranspirations increase.

ii. The correlation between EV0 and EVP is always very high (0.9 or higher), which, under scarcity of data, suggests the possibility to estimate EV0 based on EVP.

The first conclusion anticipates that the application of Thornthwaite-Mather water balance model would yield rather distinct estimates of the surface runoff when based upon on EVP or on EV0.

In the previous scope, **Figure 4** shows the comparison between monthly streamflows (expressed in water depth) from the water balance model based on the monthly potential evapotranspiration of Thornthwaite (HP) and of Penman-Monteith (H0). Such results were obtained assuming a maximum useable water capacity of the soil (Smax) of 150 mm that allegedly corresponds to the average conditions prevalent in Mainland Portugal, though, in fact, the values of Smax are expected to be slightly higher in the southern than in the northern parts of the country.

The results from the linear regression analysis between HP and H0 are represented in each graph by a continuous straight line, its equation, and the corresponding correlation coefficient, r. The graph also includes a dashed straight line representing the equality between HP and H0. The scale of the axes is always the same in order to allow the comparison between the two surface runoffs and among the different climatological stations.

It is important to emphasize that, for most of the climatological stations, the high values shown in **Figure 4** for the linear correlation coefficient indicate a statistically significant dependency between monthly streamflows evaluated on the basis of Thornthwaite (HP) and Penman-Monteith (H0) evapotranspiration. As the potential evapotranspiration of Thornthwaite (EVP) is always lower than the potential evapotranspiration of Penman-Monteith (EV0), its derived monthly streamflows (HP) are sometimes higher, although only slightly, than those provided by the Penman-Monteith data (H0).

However, significant differences between potential evapotranspirations, as those shown in **Figure 3**, may not necessarily lead to substantial differences between surface runoff evaluated based on those evapotranspirations. This is the case of the climatologic stations of Bragança (03Q/01), Mirandela (05T/01), Vila Real (06K/01), Régua (07K/01), Viseu (10J/01), Coimbra-Bencanta (12G/06), Alcobaça/E. Fruticultura (16D/06), Ota (19D/01), and Sassoeiros (21B/03), where the monthly surface runoffs obtained by the water balance model considering either EVP or EV0 are very close, regardless of the differences between evapotranspirations.

This highly interesting, and innovative observation can be explained by the fact that the largest differences between monthly values of EVP and EV0 occur in the dry semester—from April to September—during which the water excess (or *superavit*) and, consequently, the surface runoff are no longer controlled by the evapotranspiration. They are a consequence, instead, of the combined effect of low or even nonexisting rainfall and groundwater storage.

This effect results in an actual evapotranspiration that is rather unrelated to the potential one since it is limited not by the "potentiality" of the soil and plants to transfer water to the atmosphere, but, instead, by the scarcity of water that inhibits that "potentiality." Under these circumstances, the actual evapotranspirations derived considering either EVP or EV0 become very close even when these potential evapotranspirations are quite different.

Figure 5 intends to demonstrate the previous conclusion, based on the climatological stations of Vila Real (06K/01), Alcobaça/E. Fruticultura (16D/06), and Viseu (10J/01) chosen as examples.

For each of the stations adopted as examples and for each month, **Figure 5** shows the monthly averages and the standard deviations of the series of EVP and of EV0 and of the surface runoffs predicted by applying the Thornthwaite-Mather water balance model to those evapotranspirations (HP and H0, respectively).

The previous figure shows that, on average, the monthly values of EVP are always lower than those of EV0, the differences being larger in the summer period.

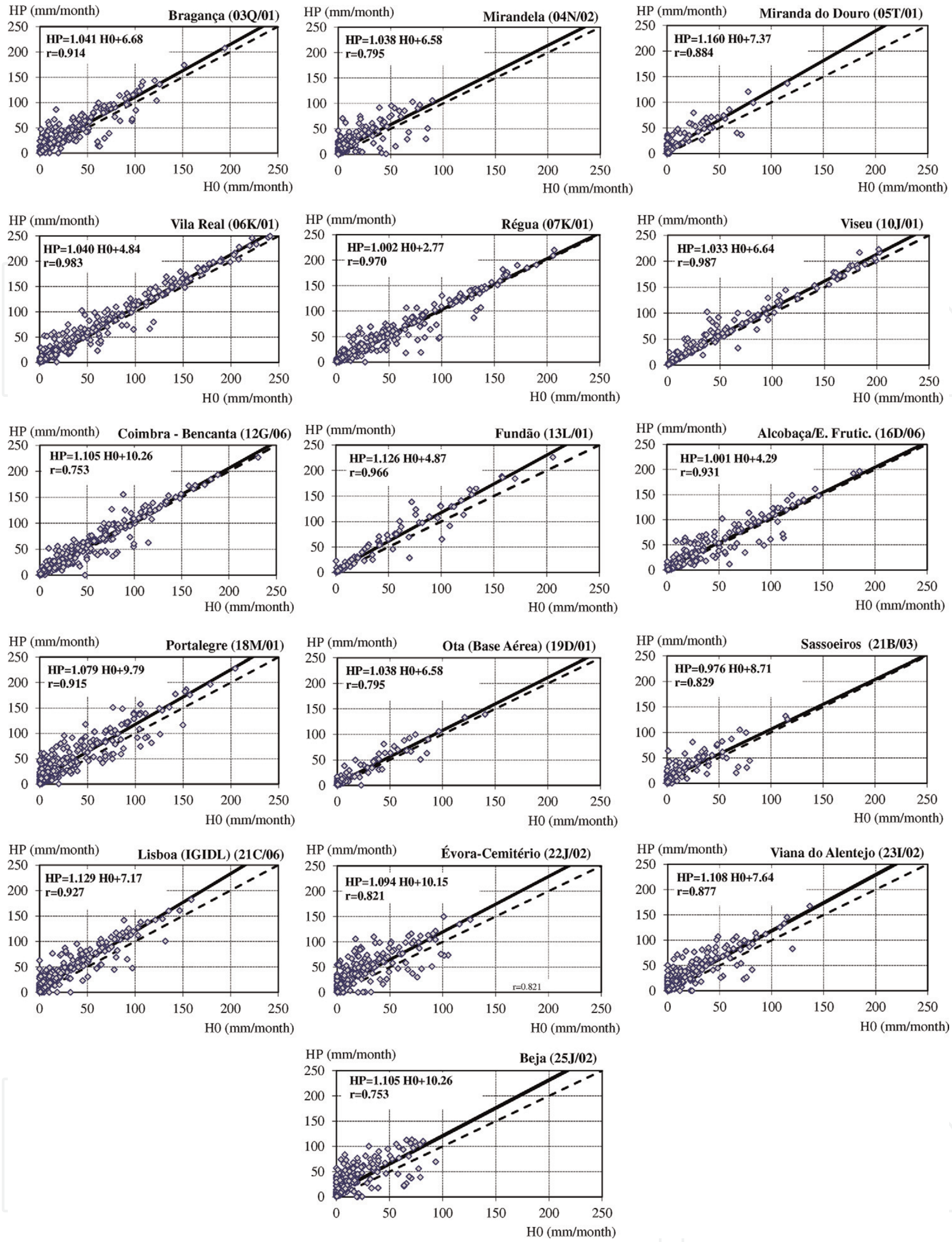

Figure 4.
Monthly flows predicted by the monthly Thornthwaite-Mather water balance model applied to the monthly evapotranspirations of Thornthwaite (HP) and of Penman-Monteith (H0). Linear regression line (continuous line), equation, and correlation coefficient, r. Line representing the equality between monthly HP and H0 (dashed line).

However, even during this season, the differences between the monthly mean surface runoffs HP and H0 are very small.

It is also important to stress that the month-by-month variability of the EVP series is larger than the one of the EV0 series (higher standard deviations). Despite this fact, the within-the-year variability of the flow series obtained from both evapotranspirations is very similar, meaning that the water balance model applied to ETP or ET0 yields to monthly streamflows that are very similar, either in value or in what concerns their statistical characteristics.

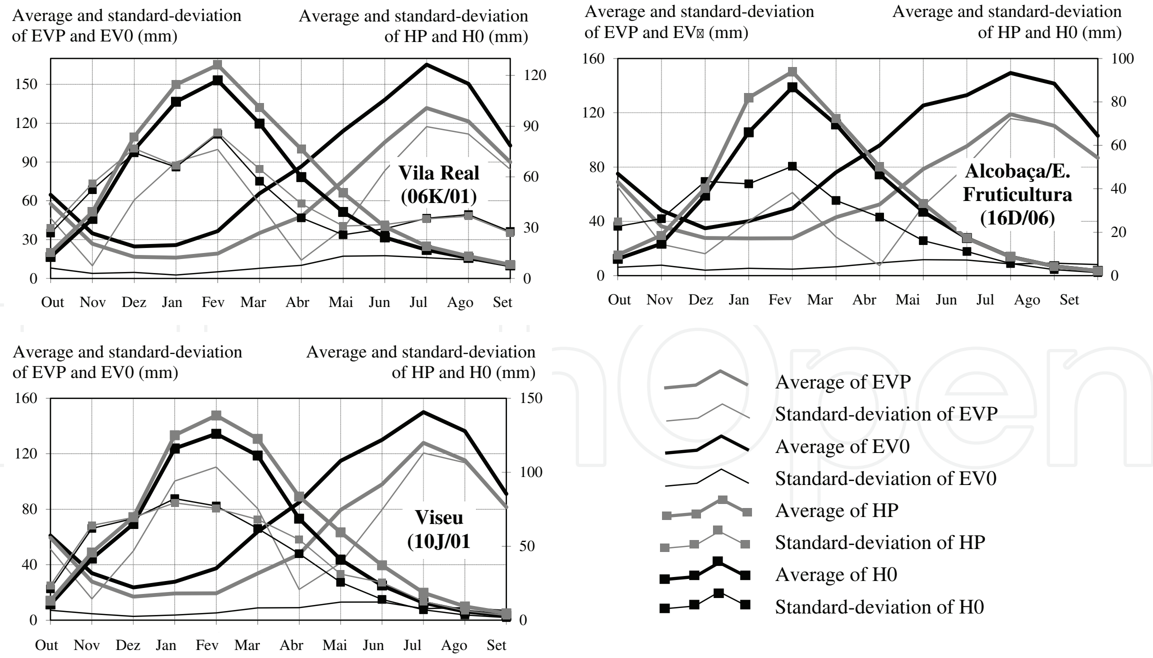

Figure 5.
Averages and standard deviation of the monthly series of EVP, EV0, HP, and H0 in some of the climatologic stations of ***Table 1****.*

5. Conclusions

The main conclusions of this study are as follows:

i. The method of Thornthwaite yields to monthly potential evapotranspirations clearly smaller than those resulting from the Penman-Monteith method, thus confirming that the former method underestimates the potential evapotranspiration in Mainland Portugal. Nevertheless, the Thornthwaite and Penman-Monteith monthly potential evapotranspirations are highly correlated.

ii. For most of the studied climatological stations, the Thornthwaite water balance model resulted in monthly surface runoffs based on the evapotranspiration of Thornthwaite slightly higher than those resulting from the Penman-Monteith evapotranspiration. However, the correlation coefficients between surface runoffs obtained via one or the other potential evapotranspiration are most of the time very high.

iii. The differences between monthly surface runoffs obtained by the water balance model considering the Thornthwaite or the Penman-Monteith potential evapotranspirations are much smaller than the differences between those evapotranspirations and may even become negligible, particularly in the wetter areas of Portugal.

According to the previous results, one may conclude that, despite its poor data requirements, the potential evapotranspiration of Thornthwaite combined with the simplest water balance model provides a feasible and accurate approach (i) to fill in the gaps of monthly flow series, (ii) to increase the spans of such series, and (iii) to estimate monthly flows at ungauged catchments.

Through regression analysis techniques, it is also possible to derive the monthly Penman-Monteith potential evapotranspiration from the Thornthwaite one and then to apply the Thornthwaite water balance model or another model to estimate the surface runoff, like the Temez model. By this way, the overestimation of surface runoff that may result from the direct use of EVP, particularly in dryer regions, will be corrected.

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Conflict of interest

The authors declare that they have no conflict of interest.

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