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EFFECT OF ACTUAL VAPOR PRESSURE ON ESTIMATING EVAPOTRANSPIRATION AT SERBIA

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Abstract. *Actual vapor pressure (VP) is an important parameter that is used in many evapotranspiration equations. However, vapor pressure is difficult to measure accurately. In the humid climate, the actual vapor pressure can be derived from minimum air temperature. The objectives of this study were: first, to estimate errors that can arise if VP data are not available and have to be estimated; second, to compare the Priestley-Taylor ET0 values computed under various levels of VP data availability; and third, to evaluate the reliability of Priestley-Taylor equation as compared to the FAO-56 Penman-Monteith method. The following main conclusions can be drawn: Estimated VP values generally were in closest agreement with measured VP values. The measurements of air humidity at humid locations are not indispensable for estimating reference evapotranspiration. The Priestley-Taylor method (with measured or estimated VP) provides the very good agreement with the evapotranspiration obtained by the FAO-56 Penman-Monteith method except windless locations.*

Key words: *Vapor pressure, Reference evapotranspiration, FAO-56 Penman-Monteith, Priestley-Taylor*

1. INTRODUCTION

Accurate estimation of evapotranspiration is required for efficient irrigation management. Evapotranspiration is a complex process because it depends on several weather factors, such as temperature, radiation, humidity, wind speed and type and growth stage of the crop.

Actual vapor pressure (VP) is an important parameter that is used in many evapotranspiration equations (Trajković i Stojnić 2004, Trajkovic and Kolakovic 2009). However, vapor pressure is difficult to measure accurately. Measurements of relative humidity by electronic sensors are commonly plagued by hysteresis, nonlinearity and calibration errors (Allen 1996). In the humid climate, the actual vapor pressure can be derived from minimum air temperature (T_{min}) (Jensen et al. 1997; Kimball et al. 1997; Thornthon et al. 2000)

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The objectives of this study were: first, to estimate errors that can arise if VP data are not available and have to be estimated; second, to compare the Priestley-Taylor ET_0 values computed under various levels of VP data availability; and third, to evaluate the reliability of Priestley-Taylor equation as compared to the FAO-56 Penman-Monteith method.

2. METHODS AND MATERIALS

2.1. Climatic data

The six humid weather stations selected for this study are located in Serbia. These locations are Palic, Novi Sad, Negotin, Kragujevac, Nis, and Vranje. Temperature, wind speed, humidity, vapor pressure, and sunshine hours were collected at these stations for different time periods. Values of these weather parameters were obtained from Federal Meteorological Service. The description of the different weather stations along with the observation periods, number of patterns and mean weather data is given in Table 1. These locations were chosen because: first, they have high quality weather data; second, they cover all the humid latitudes in Serbia (from 43 ^{o}N to 46 ^{o}N) and third, they are situated on the different heights above the sea level.

Table 1. Summary of Weather Station Sites Used in Study

Station (1)	Latitude (^{o}N) (2)	Altitude (m) (3)	Period (4)	Patterns (5)	T_{max} (^{o}C) (6)	T_{min} (^{o}C) (8)	RH (%) (10)	U_2 (m s^{-1}) (12)	ET_{0_pm} (mm d^{-1}) (13)	pET_{0_pm} (mm d^{-1}) (14)
Palic	46.1	102	1977-83	84	15.5	6.1	74	1.7	2.2	4.4
Novi Sad	45.3	86	1981-84	48	16.2	6.3	74	1.9	2.3	4.4
Negotin	44.2	42	1971-74	48	16.3	5.9	74	1.7	2.3	4.8
Kragujevac	44.0	190	1981-84	48	16.4	6.0	75	1.1	2.1	4.2
Nis	43.3	202	1977-84	96	17.0	6.2	71	1.0	2.2	4.3
Vranje	42.6	433	1971-74	48	15.9	5.7	72	1.5	2.3	4.5

Differences in the mean weather data for these locations are not very significant. The mean annual maximum and minimum temperatures (T_{max} and T_{min}) for all locations varied between 15.5 and 17.0 ^{o}C and 5.7 and 6.3 ^{o}C, respectively, and they were highest at Nis (1977-84; 17.0 ^{o}C) and Novi Sad (1981-84; 6.3 ^{o}C), respectively. The mean maximum and minimum temperatures for peak month (pT_{max} and pT_{min}) for these locations ranged from 26.1 to 28.4 ^{o}C and from 14.0 to 15.6 ^{o}C, respectively. The mean relative humidity for the peak month (pRH) varied between 71 and 75% for all locations. The mean annual wind speed (U_2) was the lowest at Nis (1977-84; 1.0 m s^{-1}) and Kragujevac (1981-84; 1.1 m s^{-1}); it varied for all other locations between 1.5 and 1.9 m s^{-1}. The mean annual and peak monthly estimates by FAO-56 PM method (ET_{0_pm} and pET_{0_pm}) ranged from 2.1 to 2.3 mm day^{-1} and 4.2 to 4.8 mm day^{-1}, respectively.

2.2. ET_0 equations

Allen et al. (1998) defined the reference evapotranspiration (ET_0) as "the rate of evapotranspiration from hypothetical crop with an assumed crop height (0.12 m) and a

fixed canopy resistance (70 s m^{-1}) and albedo (0.23) which would closely resemble evapotranspiration from an extensive surface of green grass cover of uniform height, actively growing, completely shading the ground and not short of water".

The International Commission for Irrigation and Drainage (ICID) and Food and Agriculture Organisation of the United Nations (FAO) have proposed using the Penman-Monteith method as the standard method for estimating reference evapotranspiration, and for evaluating other methods (Allen et al. 1994 a, b).

FAO-56 Penman-Monteith (FAO-56 PM) equation is (Allen et al. 1998):

$$ET_0 = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \frac{900}{T + 273} U_2 \cdot VPD)}{\Delta + \gamma \cdot (1 + 0.34 U_2)} \tag{1}$$

where ET_0 = reference evapotranspiration (mm day^{-1}); Δ = slope of the saturation vapor pressure function (kPa $^oC^{-1}$); R_n = net radiation (MJ m^{-2} day^{-1}); G =soil heat flux density (MJ m^{-2} day^{-1}); γ = psychometric constant (kPa $^oC^{-1}$); T = mean air temperature (^oC); U_2 = average 24-hour wind speed at 2 meters height (m s^{-1}); VPD = vapor pressure deficit (kPa).

Priestley-Taylor equation is often used to estimate ET_0 at the humid locations (Priestley-Taylor 1972). This equation is of the form:

$$ET_0 = \alpha \frac{\Delta}{\Delta + \gamma} (R_n - G) \tag{2}$$

where α = proportionality constant (α = 1.26).

Priestley-Taylor equation usually neglected the soil heat flux G for daily or monthly estimates of ET_0 and computed net radiation using following equation:

$$\begin{gathered} R_n = 0.77 \cdot (0.25 + 0.5 \frac{n}{N}) \cdot R_a - \\ 2.45 \cdot 10^{-9} (0.9 \frac{n}{N} + 0.1) \cdot (0.34 - 0.14 \sqrt{VP}) \cdot (T_{max,k}{}^4 - T_{min,k}{}^4) \end{gathered} \tag{3}$$

where: R_a = extraterrestrial radiation (MJ m^{-2} day^{-1});VP = actual vapor pressure (kPa); $T_{max,\,k}$ = maximum air temperature (^oK); and $T_{min,k}$ = minimum air temperature (^oK).

Priestley-Taylor method for estimating ET_0 from weather data requires following weather data: minimum (T_{min}) and maximum air temperature (T_{max}), sunshine hours (n) and actual vapor pressure (VP). The actual vapor pressure can be derived from minimum air temperature (T_{min}) according to the following equation:

$$VP = 0.611 \exp\left[\frac{17.27 T_{min}}{T_{min} + 237.3}\right] \tag{4}$$

3. Results and Discussion

The mean monthly measured (VP) and estimated vapor pressure VP(T_{min}) values for peak month and average year are shown in Table 2. This table also presents the corresponding R_n and ET_o values obtained using measured and estimated vapor pressure. In this table, $R_{n,\ tnu}$ and $ET_{o,\ tnu}$ denote R_n and ET_o values obtained from estimated VP, respectively.

At all locations estimated VP values fairly well paralleled the measured VP data. The relative error varied from –4% (Kragujevac) to 2% (Vranje) for the entire year. It ranged from –3.1% (Kragujevac) to 5.6% (Palic and Vranje) for the peak month (July).

R_n values calculated with estimated VP (Rn, tnu) were in excellent agreement with corresponding Rn values calculated from the full weather data set. The highest annual error of 0.7% was observed at Kragujevac. As a result, difference between ET_0 values obtained with estimated VP and ET_0 calculated from the full weather data was very low. The error ranged from –0.8% (Vranje) to 1.9% (Negotin) for entire year. It varied from –2.2% (Palic) to 0.1% (Novi Sad) for the peak month. It was interesting to note that at all locations a very low error in prediction of ETo arises by assuming Tmin reaches dew point. The measurements of air humidity could be omitted at humid locations because the estimated VP values enable acceptable estimating ETo when measured vapor pressure data are not available.

The comparison between measured and estimated actual vapor pressure for Novi Sad is shown in Figure 1. Estimated VP values fairly well paralleled the measured VP data.

Table 2. Statistical Summary of VP, R_n and ET_0 Estimates for Six Locations in Serbia

Mean (1)	VP (kPa) (2)	VP(T_{min}) (kPa) (3)	VP(T_{min}) /VP (4)	$R_{n,tnu}$ /R_n (5)	$ET_{0\_pm,tnu}$ / ET_{0_pm} (6)
Palic (1977-83)					
peak month	1.611	1.702	1.056	1.009	0.978
annual	1.022	1.036	1.014	1.003	1.001
Novi Sad (1981-84)					
peak month	1.685	1.675	0.994	0.999	1.001
annual	1.054	1.045	0.991	0.999	1.010
Negotin (1971-74)					
peak month	1.720	1.770	1.029	1.005	0.989
annual	1.053	1.025	0.973	0.996	1.019
Kragujevac (1981-84)					
peak month	1.647	1.596	0.969	0.995	1.004
annual	1.044	1.002	0.960	0.993	1.012
Nis (1977-84)					
peak month	1.567	1.621	1.034	1.005	0.992
annual	1.004	1.023	1.019	1.004	0.993
Vranje (1971-74)					
peak month	1.517	1.602	1.056	1.008	0.979
annual	0.971	0.990	1.020	1.005	0.992

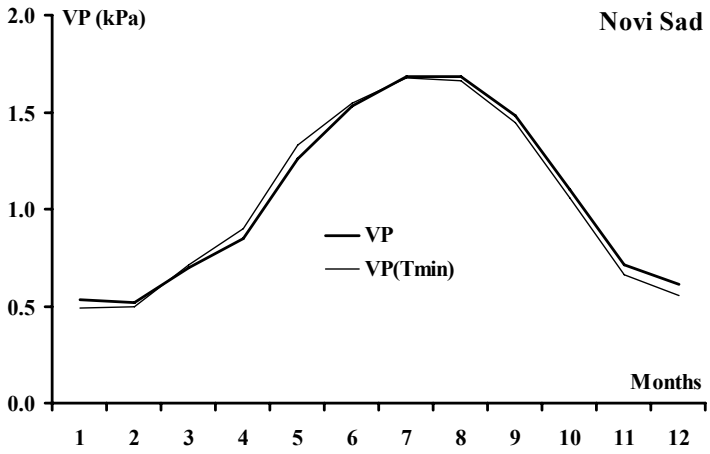

Fig. 1 Mean Monthly Vapor Pressure for Novi Sad (1981-1984)

Table 3 summarizes the statistical analysis between monthly FAO-56 PM ET_0 estimates (ET_{0_pm}) and Priestley-Taylor estimates obtained with measured (ET_{0_pt}) or estimated VP ($ET_{0\_pt,tn}$) for the six humid locations. Standard errors of estimate (SEEs) were calculated as follows:

$$SEE = \left[\frac{\sum_{i=1}^{l} (ET_{0\_pm,i} - ET_{0\_method,i})^2}{l-1} \right]^{0.5} \tag{5}$$

where SEE = standard error of estimate (mm day^{-1}); ET_{0_pm} = ET_0 estimated by the standard (FAO-56 PM) method (mm day^{-1}); ET_{0_method} = corresponding ET_0 estimated by the comparison method (mm day^{-1}); and l = total number of observations. Standard error of estimate indicates how well each method estimated reference evapotranspiration over all months of record.

Priestley-Taylor estimates obtained with measured (ET_{0_pt}) or estimated VP ($ET_{0\_pt,tn}$) were in fairly well agreement with FAO-56 PM estimates for all stations. These methods underpredicted mean annual ET_0 at all locations except Nis and Kragujevac and overpredicted mean ET_o for the peak month at all locations. The highest overestimation for the peak month was observed at Kragujevac and Nis (13% and 12% respectively). This overestimation may be due to low wind speed at these locations. The highest SEEs were calculated at Kragujevac (0.33 mm day^{-1} for both methods). The lowest SEEs were found at Vranje (0.23 mm day^{-1} for both methods). The mean daily FAO-56 Penman-Monteith (ET_{0_pm}), and Priestley-Taylor estimates obtained with measured (ET_{0_pt}) or estimated VP ($ET_{0\_pt,tn}$) for Vranje are plotted in Figure 2. Priestley-Taylor estimates obtained with measured (ET_{0_pt}) or estimated VP ($ET_{0\_pt,tn}$) paralleled FAO-56 PM ET_0 values during the entire period (1971-74) at Vranje except (for) June and July of 1983. Main reason for

the overprediction may be due to lower wind speed and lower vapor pressure deficits in these months. Overall, the Pristley-Taylor method (with measured or estimated VP) was found to be in very good agreement with FAO-56 PM method in humid locations, making it the good predictor.

Table 3. Statistical Summary of ET_0 Estimates for Six Locations in Serbia

Method (1)	Peak month (mm day^{-1}) (2)	Mean annual (mm day^{-1}) (3)	$pET_{0\_pt(tn)}$ /p ET_{0_pm} (4)	$ET_{0\_pt(tn)}$ /ET_{0_pm} (5)	SEE (mm day^{-1}) (6)
Palic (1977-83)					
ET_{0_pt}	4.62	2.17	1.06	0.98	0.243
$ET_{0\_pt,tn}$	4.66	2.18	1.07	0.98	0.254
Novi Sad (1981-84)					
ET_{0_pt}	4.67	2.21	1.07	0.95	0.321
$ET_{0\_pt,tn}$	4.66	2.21	1.07	0.95	0.320
Negotin (1971-74)					
ET_{0_pt}	4.97	2.29	1.03	0.98	0.277
$ET_{0\_pt,tn}$	5.00	2.28	1.03	0.98	0.280
Kragujevac (1981-84)					
ET_{0_pt}	4.76	2.20	1.13	1.05	0.332
$ET_{0\_pt,tn}$	4.73	2.19	1.13	1.04	0.329
Nis (1977-84)					
ET_{0_pt}	4.78	2.27	1.11	1.03	0.305
$ET_{0\_pt,tn}$	4.80	2.28	1.12	1.03	0.311
Vranje (1971-74)					
ET_{0_pt}	4.67	2.28	1.04	0.99	0.232
$ET_{0\_pt,tn}$	4.70	2.30	1.05	0.99	0.229

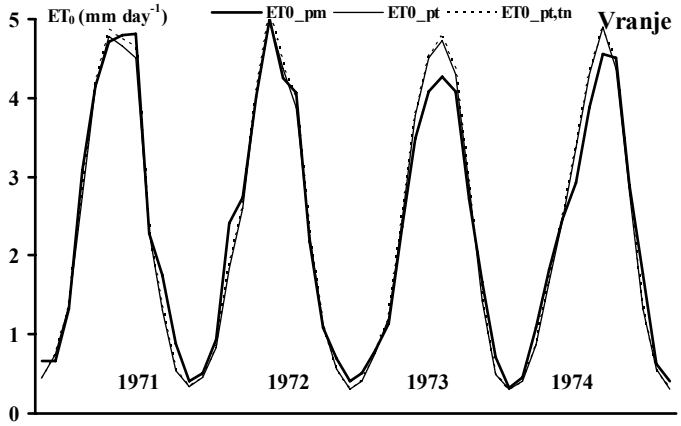

Fig. 2 The mean daily FAO-56 Penman-Monteith and Priestley-Taylor estimates

4. CONCLUSIONS

The following main conclusions can be drawn:

Estimated VP values generally were in closest agreement with measured VP values. At all locations the very low error in estimating ETo arises by assuming minimum air temperature reaches dew point. The measurements of air humidity at humid locations are not indispensable for estimating reference evapotranspiration. The Priestley-Taylor method (with measured or estimated VP) provides the very good agreement with the evapotranspiration obtained by the FAO-56 Penman-Monteith method except windless locations. The convincing results recommended this method for estimating reference evapotranspiration in humid Serbian locations. The results are of significant practical use because the Priestley-Taylor method can be used when relative humidity and wind speed data are not available.

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UTICAJ STVARNOG PRITISKA VODENE PARE NA PRORAČUN EVAPOTRANSPIRACIJE U SRBIJI

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Vlažnost vazduha jedan je od najvažnijih klimatskih faktora koji odredjuju proces evapotranspiracije. Stvarni napon vodene pare se izražava preko temperature tačke rose. U humidnoj klimi se ova vrednost može zameniti minimalnom dnevnom temperaturom. Ciljevi ovog rada su bili da se procene odstupanja koja se mogu desiti ako ne koristimo merene vrednosti stvarnog napona vodene pare (VP), da se uporede Priestley-Taylor (PT) ET_0 vrednosti dobijene sa i bez merenih VP vrednosti i da se proceni pouzdanost

PT metode u poredjenju sa standardnom FAO-56 PM metodom. Sledeći glavni zaključci se mogu izvesti iz ovog istraživanja: Sračunate VP vrednosti su, generalno, veoma bliske merenim VP vrednostima. Merenja relativne vlažnosti nisu neophodna za proračun referentne evapotranspiracije u humidnoj klimi Srbije. PT metoda obezbedjuje veoma dobro slaganje sa FAO-56 PM metodom izuzev lokacija sa malom brzinom vetra.

Ključne reči: *Pritisak vodene pare, Referentna evapotranspiracija, FAO-56 Penman-Monteith, Priestley-Taylor*