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MINIMUM WEATHER DATA REQUIREMENTS FOR ESTIMATING REFERENCE EVAPOTRANSPIRATION

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Abstract. *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 (ET_0), and for evaluating other methods. The FAO-56 Penman-Monteith (FAO-56 PM) method requires the numerous weather data that are not available in the most of the stations. The objectives of this study were: first, to estimate errors that can arise if some weather data are not available and have to be estimated; second, to compare the FAO-56 PM ET_0 values computed under various levels of data availability; and third, to determine minimum weather data requirements for estimating ET_0 without decreasing the acceptable accuracy. For this study, full weather data sets were collected from six humid weather stations from Serbia (Southeast Europe).The main conclusion is that the minimum and maximum air temperature and "local default" value of wind speed are the minimum data requirements necessary to apply the FAO-56 PM method in humid climate.*

Key words: *Reference evapotranspiration, Penman-Monteith, Air temperature, Solar radiation, Relative humidity, Wind speed.*

1. INTRODUCTION

Evapotranspiration (ET) is one of the major components in the hydrological cycle, and its reliable estimation is essential to water resources planning and management. A common procedure for estimating evapotranspiration is to first estimate reference evapotranspiration (ET_0) and then apply a corresponding crop coefficient. Reference evapotranspiration is defined in Allen et al. (1998) as "the rate of evapotranspiration from hypothetical crop with an assumed crop height (0.12 m) and a fixed canopy resistance

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(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". Crop coefficients, which depend on the crop characteristics and local conditions, are then used to convert ET_0 to the ET. This paper addresses only the estimation of ET_0.

Jensen et al. (1990) analysed the properties of twenty different methods against carefully selected lysimeter data from eleven stations located worldwide in different climates. The Penman-Monteith (PM) method ranked as the best method for estimating daily and monthly ETo for all climates.

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).

The FAO-56 Penman-Monteith (FAO-56 PM) method computes ET_0 according to the following equation (Allen et al., 1998):

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

where ET_0 = grass reference evapotranspiration (mm d^{-1}); Δ = slope of the saturation vapor pressure function (kPa $^0C^{-1}$); Rn = net radiation (MJ m^{-2} d^{-1}); G = soil heat flux density (MJ m^{-2} d^{-1}); γ = psychometric constant (k Pa $^0C^{-1}$); T = mean air temperature (^{0}C); U_2 = average 24-hour wind speed at 2 m height (m s^{-1}); and VPD = vapor pressure deficit (kPa).

The results of several latest studies supported use of this method for ETo estimation (Todorovic 1999, Ventura et al. 1999, Trajkovic 2005, Gavilan et al. 2007). The FAO-56 Penman-Monteith method requires numerous weather data that are not available in the most of the stations. In the absence of a full data set, Annandale et al. (2002) still advises using the FAO-56 PM method, but with recommended procedures for calculating missing weather data.

The objectives of this study were: first, to estimate errors that can arise if some weather data are not available and have to be estimated; second, to compare the FAO-56 PM ET_0 values computed under various levels of data availability; and third, to determine minimum weather data requirements for estimating ET_0 without decreasing the acceptable accuracy. This research indicates how important it is to measure all of the parameters affecting ET_0, and under which conditions the FAO-56 procedures for estimating missing data give desired accuracy.

2. WEATHER DATA

The FAO-56 Penman-Monteith method for estimating reference evapotranspiration from weather data requires following weather data: net radiation (Rn), actual vapor pressure (VP), wind speed at 2 m height (U), and minimum and maximum air temperature (Tmin and Tmax, respectively).

2.1. Net radiation

The net radiation (Rn) is the primary driver of the evapotranspiration process and Rn data are an integrated part of many ET estimation procedures. However, net radiation is an infrequently measured weather parameter, compared to temperature and sunshine hours.

Another problem is that the net radiometers are the most delicate of the sensors used in weather stations. They are very expensive and they deteriorate rapidly in comparison with other sensors (Llasat and Snyder, 1998). As a result, net radiation is often estimate from other parameters. The parameters that are used in the Rn estimates include minimum and maximum air temperature (Tmin and Tmax, respectively), actual vapor pressure (VP), and solar radiation (Rs) or sunshine hours (n).

The solar radiation (Rs) is measured by pyranometers or actinometers. However, there are many weather stations, which do not measure solar radiation (Meza and Varas 2000). In the USA one out of a hundred stations measures the solar radiation and globally the ratio is 1:500 (Thornton and Running, 1999) that corresponds to the data from Australia, where out of 16,000 stations only 50 stations measure the solar radiation (Liu and Scott, 2001). Where Rs data are not available, solar radiation is usually estimated from measured sunshine hours.

$$Rs = \left(0.25 + 0.5\frac{n}{N}\right)Ra \qquad (2)$$

where n = actual duration of sunshine (hour); N = maximum possible duration of sunshine (hour); and Ra = extraterrestrial radiation (MJ m^{-2} d^{-1}).

Allen et al. (1998) suggested that net radiation be computed using following equation:

$$Rn = 0.77(0.25 + 0.5\frac{n}{N})Ra - 2.45 \cdot 10^{-9}(0.9\frac{n}{N} + 0.1)(0.34 - 0.14\sqrt{VP})(T\max,k^4 - T\min,k^4) \qquad (3)$$

where Rn = net radiation (MJ m^{-2} d^{-1}); VP = actual vapor pressure (kPa); Tmax,k = maximum air temperature (^{0}K); and Tmin,k = minimum air temperature (^{0}K).

However, if sunshine hours are not measured, solar radiation data can be derived from air temperature differences (Hargreaves et al., 1985; Allen, 1997; Samani, 2000):

$$Rs(T) = K\sqrt{(T\max - T\min)}Ra \qquad (4)$$

where *Rs*(*T*) = solar radiation estimated from air temperature differences (MJ m^{-2} d^{-1}); and *K* = adjustment coefficient.

In this case, the net radiation can be obtained from following equation:

$$Rn\,(T) = 0.77Rs(T) - 2.45 \cdot 10^{-9}(1.35\frac{Rs(T)}{(0.75 + 2 \cdot 10^{-5}z)Ra} - 0.35)(0.34 - 0.14\sqrt{VP})(T\max,k^4 - T\min,k^4) \qquad (5)$$

where *z* = altitude (m).

2.2. Actual vapor pressure

The actual vapor pressure (VP) is defined as the saturation vapor pressure at dew point temperature (Tdew), or:

$$VP = 0.611 \exp\left[\frac{17.27 Tdew}{Tdew + 237.3}\right] \tag{6}$$

If air humidity data are not available, an estimate of VP can be made by assuming minimum air temperature is equal to dew point temperature (Jensen et al., 1997; Thornton, et al. 2000). If Tmin is used to represent Tdew then:

$$VP(T\min) = 0.611 \exp\left[\frac{17.27 T\min}{T\min + 237.3}\right] \tag{7}$$

2.3. Wind speed

Wind speed is one of the least easily estimated and least available parameters needed for estimating ET_0. Wind speed is not routinely measured at many weather stations and may need to be estimated when Penman-Monteith ET_0 equation is applied. The common alternative is to use "default" wind speed, which can be calculated as the average wind speed for the long-term period.

2.4. Air temperature

Air temperature is the essential weather parameter for estimating reference evapotranspiration. Many of the suggested procedures for estimating other parameters rely upon maximum and minimum air temperature measurements. These measurements are simple and are not subject to high errors as opposed to the other weather parameters. Also the air temperature is measured at almost all the stations and these data are easily accessed. There is no dependable way to estimate air temperature when it is missing.

3. Missing Data Error Analysis

For this study, full weather data sets were collected from six humid weather stations from Serbia (Southeast Europe). These locations are Vranje, Nis, Negotin, Valjevo, Novi Sad, and Palic. All weather data set included maximum air temperature; minimum air temperature; sunshine hours, actual vapor pressure and wind speed. Values of these weather parameters were obtained from Federal Meteorological Service. Each station is equipped with mercury and alcohol thermometers, a Campbell-Stokes sunshine recorder, an anemometer at 10 m, and a psychrometer. Weather data included daily values of following parameters averaged over each month: maximum air temperature; minimum air temperature; actual vapor pressure, wind speed and sunshine hours. There are no measured radiation data. The description of the selected weather stations along with the observation periods, number of patterns and average weather data is given in Table 1.

Differences in the weather data for these locations are not very significant. The annual average maximum and minimum temperatures (Tmax and Tmin) for all locations varied between 15.5 and 17.0 ^{0}C and 5.8 and 6.3 ^{0}C, respectively. The average wind speed (U2) was the lowest at Valjevo (U2 = 0.5 m s^{-1}); it ranged for all other locations between 1.0 to 1.9 m s^{-1}. The average relative humidity (RH) varied between 71 and 79 % and the average FAO-56 Penman Monteith ET0 ranged from 2.0 to 2.3 mm day^{-1}.

Table 1. Summary of Weather Station Sites Used in Study

Station	Latitude (^{0}N)	Altitude (m)	Period	Patterns	T_{max} (^{0}C)	T_{min} (^{0}C)	RH (%)	U_2 (m s^{-1})	ET_0 (mm d^{-1})
Palic	46.1	102	1977-83	84	15.5	6.1	74	1.7	2.2
Novi Sad	45.3	86	1981-84	48	16.2	6.3	74	1.9	2.3
Valjevo	44.3	174	1981-84	48	16.8	5.8	73	0.5	2.0
Negotin	44.2	42	1971-74	48	16.3	5.9	74	1.7	2.3
Nis	43.3	202	1977-84	96	17.0	6.2	71	1.0	2.2
Vranje	42.6	433	1971-74	48	15.9	5.7	72	1.5	2.3

3.1. Radiation

In this study, the equation (2) was chosen as a standard equation for computing solar radiation because there were no measured Rs data at any location. These estimates were compared to Rs(T) estimates. Also, mean daily Rn and ET_0 values calculated using full data set were compared with estimates of Rn and ET_0 obtained with estimated Rs(T), respectively. The mean daily Rs, Rn and ET_0 values obtained by averaging the daily values across the period of record for each of the six humid locations are summarized in Table 2. In this table, ET_0_pm,teu denotes ET_0 values obtained from estimated Rn(T).

Table 2. Statistical Summary of Rs, Rn and ET_0 Estimates for Six Locations in Serbia

Mean (1)	Rs (MJ m^{-2} d^{-1}) (2)	Rs(T) (MJ m^{-2} d^{-1}) (3)	Rs(T)/Rs (4)	R_n(T)/R_n (5)	$ET_{0\_pm,teu}$/ ET_{0_pm} (6)
		Palic (1977-83)			
peak month	21.62	21.52	1.00	1.00	1.00
annual	12.85	13.16	1.02	1.01	1.01
		Novi Sad (1981-84)			
peak month	21.64	22.32	1.03	1.03	1.02
annual	12.82	13.71	1.07	1.04	1.02
		Negotin (1971-74)			
peak month	22.87	23.16	1.01	1.01	1.01
annual	13.16	14.23	1.08	1.05	1.03
		Valjevo (1981-84)			
peak month	22.06	22.42	1.02	1.02	1.01
annual	12.94	14.38	1.11	1.06	1.05
		Nis (1977-84)			
peak month	22.41	23.44	1.05	1.04	1.03
annual	13.04	14.63	1.12	1.07	1.06
		Vranje (1971-74)			
peak month	21.89	22.73	1.04	1.04	1.03
annual	13.30	14.33	1.08	1.06	1.03

For all months, except for August at Vranje and Palic, the solar radiation values calculated using equation (4) (Rs(T)) were consistently higher than corresponding Rs values. The Rs(T) estimates overpredicted Rs for entire year and the peak month (July) by about 2% and 0.3%, respectively at Palic to as much as 12% and 5% at Nis. The error analysis indicated that the difference from estimating Rs by equation (4) was relatively high at Nis and Valjevo. This may be partly due to low wind speed at those locations.

The Rn(T) estimates were in closest agreement with Rn values at Novi Sad and Palic with overestimation of 1% and 4%, respectively. The highest difference of 7% was observed in Nis. Difference between net radiation calculated using equation (5) (Rn(T)) and Rn calculated from the full weather data set (equation 3) was less than corresponding difference between Rs(T) and Rs.

The ET_0 values obtained when sunshine data were not available (PM, teu) were in fairly well agreement with standard FAO-56 PM estimates. The relative difference ranged from 1% (Palic) to 6% (Nis) for the full time period. It varied from 0% (Palic) to 3% (Nis) for the peak month (July). The capacity of the equation (4) to estimate Rs is obviously not perfect. However, this equation enables acceptable estimating ET_0 when sunshine data are not available.

3.2. Vapor pressure

The mean daily measured and estimated vapor pressure values for each of three-peak summer months are shown in Table 3. This table also presents the corresponding Rn and ET_0 values obtained using measured and estimated vapor pressure. In this table, Rn, tnu and ET_0_pm,tnu denote Rn and ET_0 values obtained from estimated vapor pressure (VP(Tmin)), respectively.

Table 3. Statistical Summary of VP, Rn 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	1.61	1.70	1.06	1.01	0.98
annual	1.02	1.04	1.01	1.00	1.00
		Novi Sad (1981-84)			
peak month	1.68	1.67	0.99	1.00	1.00
annual	1.05	1.04	0.99	1.00	1.01
		Negotin (1971-74)			
peak month	1.72	1.77	1.03	1.00	0.99
annual	1.05	1.02	0.97	1.00	1.02
		Valjevo (1981-84)			
peak month	1.67	1.66	0.99	1.00	1.00
annual	1.04	1.01	0.97	0.99	1.00
		Nis (1977-84)			
peak month	1.57	1.62	1.03	1.00	0.99
annual	1.00	1.02	1.02	1.00	0.99
		Vranje (1971-74)			
peak month	1.52	1.60	1.06	1.01	0.98
annual	0.97	0.99	1.02	1.00	0.99

The estimated VP (VP(Tmin)) values fairly well paralleled the measured VP data for all months expect summer months at Vranje. The relative error varied from –3% (Negotin and Valjevo) to 2% (Vranje and Nis) for the entire year. It ranged from –1% (Novi Sad and Valjevo) to 6% (Vranje and Palic) for the peak month (July).

The Rn values calculated with estimated VP (Rn, tnu) were in excellent agreement with corresponding Rn values calculated from the full weather data set. The average annual difference for each location was low than 1%. 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 difference ranged from –1% (Vranje and Nis) to 2% (Negotin) for entire year. It varied from –2% (Vranje and Palic) to 0% (Valjevo and Novi Sad) for the peak month. At all locations a very low error in prediction of ET_0 arises by assuming Tmin reaches dew point.

The measurements of air humidity could be omitted at these humid locations because the estimated VP values enabled acceptable estimating ET_0 if measured vapor pressure data were not available.

3.3. Wind

In this study, two "default" values of wind speed were used. The "local default" values of wind speed (Ul) were calculated as the mean daily wind speed for the periods considered. These values are: 1.5 m s^{-1} for Vranje, 1.0 m s^{-1} for Nis, 1.7 m s^{-1} for Negotin, 0.5 m s^{-1} for Valjevo, 1.9 m s^{-1} for Novi Sad, and 1.7 m s^{-1} for Palic. The "regional default" value of wind speed (Ur) of 1.3 m s^{-1} was obtained as the average of twenty-three stations in Western Balkan region (Smith 1993; Trajkovic 2001).

Table 4. Statistical Summary of U_2 and ET_0 Estimates for Six Locations in Serbia

Mean (1)	U_{2_l} (m s^{-1}) (2)	U_{2_l}/U_2 (3)	$ET_{0\_pm,tenl}$ / ET_{0_pm} (4)	U_{2_r}/U_2 (5)	$ET_{0\_pm,tenr}$ / ET_{0_pm} (6)
Palic (1977-83)					
peak month	1.69	1.01	1.00	0.77	0.97
annual	1.72	0.99	1.00	0.75	0.96
Novi Sad (1981-84)					
peak month	1.66	1.15	1.02	0.79	0.97
annual	1.95	0.98	1.01	0.67	0.94
Negotin (1971-74)					
peak month	1.76	0.97	0.99	0.74	0.96
annual	1.68	1.01	1.00	0.77	0.96
Valjevo (1981-84)					
peak month	0.60	0.84	0.99	2.17	1.06
annual	0.51	0.97	1.00	2.53	1.13
Nis (1977-84)					
peak month	0.92	0.91	0.98	1.41	1.04
annual	1.03	1.03	0.98	1.26	1.05
Vranje (1971-74)					
peak month	1.62	0.93	0.99	0.80	0.97
annual	1.50	1.00	0.99	0.87	0.97

The mean daily measured and estimated wind speed values are presented in Table 4. This table also shows ET_0 values obtained using measured and estimated wind speed. In this table, ET_0, tenl and ET_0, tenr denote FAO-56 ET_0 values obtained using "local default" and "regional default" wind speed values, respectively. At all locations, a very small difference in prediction of ET_0 arises by assuming the "local default" wind speed. The relative difference ranged from -1% (Vranje) to 2% (Nis).

The "regional default" wind speed greatly overpredicted measured U for all months (153%) and for the peak month (118%) at Valjevo. For other locations, the difference between measured and estimated wind speed ranged from –33% (Novi Sad) to 26% (Nis) for entire year. The ET_0 estimates obtained using "regional default" value of wind speed were in fairly well agreement with ET_0 values calculated from the full weather data for each locations excepting Valjevo. The difference ranged from -6% (Novi Sad) to 13% (Valjevo) for the entire year. It varied from -4% (Negotin) to 6% (Valjevo) for the peak month. The measurements of wind speed may be omitted at these humid locations and the "local default" value of wind speed can be assumed. If "local default" value is not available, "regional default" value can be used. However, the difference increased by using "regional default" value of wind speed. If "regional default" wind speed is used then very poor results can be expected on locations with extreme values of wind speed.

4. Minimum Weather Data Requirements

Table 5. Statistical Summary of ET_0 Estimates for Six Locations in Serbia

Approach (1)	$ET_{0\_pm,tl}$ (2)	$ET_{0\_pm,tr}$ (3)	ET_{0_turc} (4)
Vranje (1971-74)			
ET_0 (mm d^{-1})	2.38	2.28	2.10
$ET_{0\_pm,tl}$ / ET_{0_pm}	1.03	0.98	0.91
RMSD (mm d^{-1})	0.19	0.19	0.31
Nis (1977-84)			
ET_0 (mm d^{-1})	2.33	2.42	2.15
$ET_{0\_pm,tl}$ / ET_{0_pm}	1.06	1.10	0.98
RMSD (mm d^{-1})	0.23	0.31	0.29
Valjevo (1981-84)			
ET_0 (mm d^{-1})	2.07	2.35	2.11
$ET_{0\_pm,tl}$ / ET_{0_pm}	1.05	1.19	1.07
RMSD (mm d^{-1})	0.16	0.42	0.36
Negotin (1971-74)			
ET_0 (mm d^{-1})	2.47	2.35	2.14
$ET_{0\_pm,tl}$ / ET_{0_pm}	1.06	1.01	0.92
RMSD (mm d^{-1})	0.24	0.20	0.27
Novi Sad (1981-84)			
ET_0 (mm d^{-1})	2.42	2.26	2.09
$ET_{0\_pm,tl}$ / ET_{0_pm}	1.04	0.97	0.90
RMSD (mm d^{-1})	0.18	0.14	0.33
Palic (1977-83)			
ET_0 (mm d^{-1})	2.25	2.15	2.07
$ET_{0\_pm,tl}$ / ET_{0_pm}	1.01	0.97	0.93
RMSD (mm d^{-1})	0.13	0.15	0.24
All stations			
RMSD (mm d^{-1})	0.19	0.26	0.30

Table 5 summarizes the statistical analysis between FAO-56 PM ET_0 estimates calculated using full data sets and FAO-56 reduced-set PM ET_0 values obtained with estimated Rs (Rs(T)), VP (VP(Tmin)), and U (Ul or Ur) for the six humid locations.

This table also presents statistical analysis for ET_0 calculated using Turc method. This method was selected because it was globally ranked second in humid climate (Jensen et al. 1990). In this table, ET_0_pm,tl and ET_0_pm,tr denote FAO-56 PM ET_0 estimates obtained when sunshine hours, vapor pressure and measured wind speed are not available. In these cases, "local" or "regional default" value of wind speed was used, respectively. It was interesting to note that RMSDs for all FAO-56 PM approaches calculated from incomplete data sets were found to be lower than the RMSD of Turc method with an exception of PMt,r approaches at Nis and Valjevo. The poor performance these approaches at these locations occurred because "regional default" value of wind speed was significantly higher than measured wind speed. The PMt,l estimates fairly well paralleled the PM estimates for all locations. The difference varied from +1% (Palic) to +6% (Nis and Negotin) for entire year. It ranged from –2% (Palic) to +4% (Novi Sad).

5. CONCLUSIONS

The following conclusions were drawn from the results of this analysis:

- At humid locations, the measurements of air humidity may be omitted because the estimated VP(Tmin) values enable acceptable estimating ET_0.
- Solar radiation data can be derived from air temperature differences. This procedure enables acceptable calculating ET_0 when sunshine data are not available.
- In the humid climate, the measurements of U may be omitted and the "local default" value of wind speed can be assumed. If "local default" value is not available, "regional default" value can be used. However, the difference between measured and estimated wind speed increased by using "regional default" value of wind speed.
- It was interesting to note that RMSDs for FAO-56 reduced-set PM approaches generally were found to be lower than the RMSD of Turc method. This fact strongly supports using the FAO-56 PM method even in the absence of the complete weather data set.
- The minimum and maximum air temperature and "local default" value of wind speed are the minimum data requirements necessary to apply the FAO-56 PM method in humid climate.
- The expected climate changes can greatly affect evapotranspiration. In the event the air temperature rises in the next 100 years for more than 2 °C, this will result in the increased wind speed and reduction of relative humidity in the locations in Serbia and eventually to the increase of the evapotranspiration values. See the details in Peterson and Keller 1990, Trajkovic 1998, Irmak et al. 2006, Brumbelow and Georgakakos 2007.

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PRORAČUN REFERENTNE EVAPOTRANSPIRACIJE KORIŠĆENJEM MINIMALNOG BROJA KLIMATSKIH PODATAKA

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ICID i FAO predlažu korišćenje Penman-Monteith metode kao standardne metode za proračun referentne evapotranspiracije (ET0). FAO-56 Penman-Monteith (FAO-56 PM) metoda zahteva brojne klimatske podatke koje nisu na raspolaganju na najvećem broju stanica. Osnovni cilj ovog rada je da se odredi monimalni skup klimatskih podataka koji su potrebni za pouzdani proračun referentne evapotranspiracije. Na osnovu istraživanja prikazanog u ovom radu zaključeno je da se taj skup sastoji od vrednosti minimalne i maksimalne temperature vazduha i od višegodišnje prosečnelokalne vrednosti brzine vetra.

Key words: *Referentna evapotranspiracija, Penman-Monteith, temperatura vazduha, solarna radijacija, vlažnost vazduha, brzina vetra.*