# REFERENCE EVAPOTRANSPIRATION CALCULATIONS: COMPARISONS OF SUM OF HOURLY AND DAILY TIME STEPS

Boštjan NAGLIČ[23]

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**Abstract**
Comparisons among FAO-56-PM and standardized ASCE-PM (sASCE-PM) equations for reference evapotranspiration ($ET_o$) calculations were made with a purpose to assess differences between using a daily (24 h) time step equations (FAO-56-PM and sASCE-PM-daily) and sum of hourly $ET_o$ (sASCE-PM) equation. Calculations were performed for grass reference crop using weather data from Celje-Medlog (Slovenia)agrometeorological station. The mean $ET_o$ values for investigated period of 23 successive days resulted in $ET_o$ of 3.13 mm/day for daily time step FAO-56-PM and sum of hourly sASCE-PM equations. Mean of 3.01 mm/day was observed for sASCE-PM daily time step equation. The paired *t*-test showed that mean ETo value for entire period calculated with sASCE-PM (based on daily and hourly calculations) equation were not significantly different ($P < 0.05$) from the ETo values observed with FAO-56-PM equation. This suggests that the daily and hourly time step form of standardized ASCE-PM method for ETo calculations is comparable to FAO-56-PM method for given location and time period.
**Key words:** evapotranspiration, reference evapotranspiration, Penman-Monteith method, FAO-56-PM equation, standardized ASCE-PM equation, hourly $ET_o$, agrometeorology

# IZRAČUNI REFERENČNE EVAPOTRANSPIRACIJE: PRIMERJAVA VSOTE URNIH PROTI DNEVNIM IZRAČUNOM

**Izvleček**
Narejena je bila primerjava med FAO-56-PM in standardizirano ASCE-PM enačbo za izračun referenčne evapotranspiracije z namenom, da bi ocenili razlike med uporabo dnevnega (24 h) časovnega koraka (FAO-56-PM in sASCE-PM-dnevno) in vsoto urnih vrednosti (sASCE-PM). Izračuni so bili opravljeni za referenčno površino trave ob uporabi vremenskih podatkov, zabeleženih na agrometeorološki postaji Celje-Medlog (Slovenija). Povprečne vrednosti $ET_o$ za preiskovano obdobje 23 zaporednih dni so znašale 3,13 mm/dan za metodi FAO-56-PM-dnevno in sASCE-PM-vsoto urnih vrednosti. Povprečna vrednost za sASCE PM metodo za dnevni časovni korak je znašala 3,01 mm/dan. Parni *t*-test je pokazal, da se povprečna $ET_o$ vrednost za celotno preučeno obdobje, izračunano z

[23] Dr., univ. dipl. inž. agr., Inštitut za hmeljarstvo in pivovarstvo Slovenije, Cesta Žalskega tabora 2, 3310 Žalec, Slovenia, e-pošta: bostjan.naglic@ihps.si

sASCE-PM (na podlagi dnevnih in urnih izračunov), ni pomembno razlikovala ($p < 0{,}05$) od vrednosti $ET_o$, opaženih z uporabo FAO-56-PM metode. To kaže, da je dnevna in urna časovna oblika standardizirane ASCE-PM metode za izračune $ET_o$ primerljiva s FAO-56-PM metodo za dano lokacijo in za dano časovno obdobje.
**Ključne besede:** evapotranspiracija, referenčna evapotranspiracija, Penman-Monteith metoda, FAO-56-PM enačba, standardizirana ASCE-PM enačba, urna $ET_o$, agrometeorologija

# 1 INTRODUCTION

Reference evapotranspiration ($ET_o$) is defined as the rate at which water, if readily available, would be removed from specified soil and plant surfaces (Jensen et al. 1990 cited in Itenfisu et al., 2003). When calculating crop irrigation water requirements the $ET_c$ (crop evapotranspiration) has to be calculated by multiplying $ET_o$ (reference crop evapotranspiration) with crop coefficient ($K_c$). About nine major $ET_o$ methodologies (1963 Penman, FAO-24 Penman, Kimberly Penman, CIMIS Penman, ASCE Penman-Monteith, FAO-56 Penman Monteith, Hargreaves, Jensen-Haise and pan evaporation) have been traditionally used over the last fifty years for $ET_o$ calculations. $ET_o$ equations range in sophistication from emprical solar radiation or temperature based equations (i.e. Hargreaves equation) to complex resistance based equations. The most widely used $ET_o$ equations are of combination type and most commonly include different versions of the original Penman Monteith (PM) equations (Dorenbos and Pruitt, 1977; Itenfisu et al., 2003). Because so many $ET_o$ calculation methods have been introduced this caused some confusion among researchers, growers and consultants about which method to use for $ET_o$ estimation.

In recent years advances in research and science resulted in the development of more accurate methods for assessing crop water use. Consequently it was revealed that the different $ET_o$ calculation methods did not behave the same way in different locations around the world which presented their major weakness. This unveiled the need for derivation of a standard and more consistent method for $ET_o$ calculations. For that reason in 1990 Food and Agricultural Organisation (FAO) organized a conference with scientists, experts and researchers. An outcome of this meeting was the new FAO-56 Penman-Monteith method (FAO-56-PM) which is now recommended as the standard method for calculation of the $ET_o$. This method has a good probability of correctly predicting $ET_o$ for a wide range of climates and even in the case of missing meteorological data (Allen et al., 1998; FAO, 2002).

However, when the weather stations collect or summarize hourly weather data the users sometimes need or want to calculate ET for hourly time steps. It is important that hourly summed $ET_o$ calculations closely agree with calculations made with daily time-step calculations. Hourly $ET_o$ data is important where substantial shifts in wind speed, humidity and dewpoint occur hourly. On the other hand, hourly evapotranspiration data is sometimes necessary as an input data for some numerical or analytical models that simulate water flow and root-water uptake. One such model is for instance the numerical model Hydrus (Šimůnek et al., 2006). The model has been in recent years, for instance, extensively used to simulate water distribution under surface and subsurface drip irrigation systems under cropped conditions (e.g. Aussaline, 2002; Gardenas et al., 2005; Bufon et al., 2011; Phogat et al., 2011). The FAO-56-PM equation can be also applied on an hourly basis as well, but the most accurate results can be obtained when it is used with 24-hour data (Allen et al., 1998). The equation parameters are the same in both cases.

With a reason to standardize the computation of $ET_o$ and to facilitate the use and transfer of Kc's now in use, scientists were looking for equation that can be readily modified to be equally accurate at predicting $ET_o$ for hourly and for daily time steps for particular region and climate. In response to this in 2005 the American Society of Civil Engineers (ASCE) and the Environmental and Water Resources Institute (EWRI) (ASCE-EWRI, 2005) recommended the use of standardized ASCE-Penman-Monteith method (sASCE-PM) as the representative equation for calculation of $ET_o$. This equation is derived from the full form of ASCE-PM in a very similar manner as FAO-56-PM equation was derived. Parameters in the sASCE-PM equation are different for hourly and 24 h time steps. They have also included parameters for (1) short crop (similar to 0.12 m high clipped grass) and (2) a tall crop (similar to 0.5 m high full cover alfa-alfa) which were embodied in a single equation. Itenfisu et al. (2003) analysed hourly and daily $ET_o$ data at numerous sites across USA. He compared most commonly used $ET_o$ equations for tall and short reference surfaces and the sASCE-PM equations. The sASCE-PM equation based on surface resistance of 50 s $m^{-1}$ during daytime and 200 s $m^{-1}$ during night time provided the best agreement with the full form of the ASCE-PM equation applied on a daily basis.

Accurately estimated $ET_o$ data will in irrigated agriculture become of great importance because it represents the basis for more efficient use of water and for better irrigation scheduling. Above mentioned becomes even more important by considering that a 14 % increase in irrigation water withdrawal for countries in development is expected by 2030 without taking into account impacts of climate change (Bruinsma, 2003).

In this study the daily and sum of hourly ETo values (SOH) calculated with standardized ASCE Penman-Monteith equation are compared to daily $ET_o$ values calculated with FAO-56 Penman-Monteith equation which is used by Slovenian Environmental Agency (ARSO). The ETo data is compared for one specific site located in Celje-Medlog, Slovenia. The purpose is to investigate if and how sum of hourly $ET_o$ values calculated with sASCE-PM equation for short reference crop (grass) applies to Slovenian climate conditions.

# 2 MATERIALS AND METHODS

## 2.1 Study site and climate data source

The study site was located at the Celje-Medlog, Slovenia, with coordinates 46°15'N, 15°15'W and elevation of 240 m above sea level. The site is characterised by interaction of alpine and continental climate with mild to hot summers and cold winters. The monthly average rainfall and temperatures for period 1991 – 2000 for Celje-Medlog station are presented in Table 1 (ARSO, 30.8.2013). Meteorological data needed for calculation of hourly $ET_o$ was collected for a small test dataset of 23 successive days, from 22$^{nd}$ of August to 13$^{th}$ of September 2012.

**Table 1:** Average monthly temperatures (°C) and rainfall (mm) for period 1971 to 2000 and for 2012 for agrometeorological station Celje-Medlog
**Preglednica 1:** Povprečne mesečne temperature (°C) in padavine (mm) za obdobje od 1971 do 2000 in za leto 2012 za agrometeorološko postajo Celje-Medlog

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Average temp. (°C) | -0,7 | 1.0 | 5.1 | 9.4 | 14.6 | 17.9 | 19.6 | 18.9 | 14.8 | 9.6 | 4.1 | 0.3 | 9.6 |
| Average precipitation (mm) | 49 | 52 | 70 | 77 | 90 | 134 | 132 | 123 | 109 | 117 | 102 | 76 | 1129 |
| Average temp. for 2012 (°C) | 0.7 | -3.1 | 7.8 | 10.8 | 15.2 | 20.3 | 21.4 | 20.8 | 16 | 10.6 | 8.1 | 0.2 | 10.7 |
| Monthly sum of precipitation for 2012 (mm) | 16.1 | 31.5 | 7.4 | 97.6 | 143.3 | 79.8 | 95.7 | 47.4 | 200.2 | 205.3 | 109.0 | 72.6 | 1105.9 |

Average monthly reference evapotranspiration values for 30 years period compared to average monthly values for 2012, for station Celje-Medlog, are given on Figure 1.

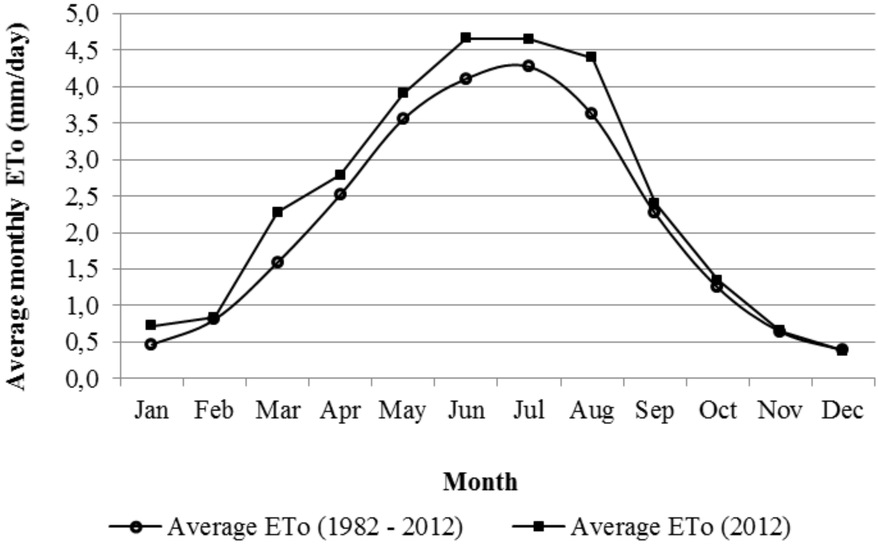


**Figure 1:** Average monthly reference evapotranspiration ($ET_o$) calculated with FAO-56-PM method for 30-years period (1982-2012) and 2012 for agrometeorological station Celje-Medlog

**Slika 1:** Povprečna mesečna referenčna evapotranspiracija ($ET_o$), izračunana z metodo FAO-56-PM za 30-letno obdobje (1982-2012) in za leto 2012 (za agrometeorološko postajo Celje-Medlog)

Daily reference evapotranspiration data for reference surface were collected and computed by ARSO using FAO-56-PM equation for daily time step. In FAO-56-PM method ETo is defined for a hypothetical grass reference crop which is not short of water, with an assumed crop height of 0.12 m, a fixed surface resistance of 70 sec/m and an albedo of 0.23 (Dorenbos and Pruitt, 1977; FAO, 2002).
FAO-56-PM equation for daily time step is given as:

$$\mathrm{ETo} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where $ET_o$ is reference evapotranspiration (mm day$^{-1}$), $R_n$ is net radiation at the crop surface (MJ m$^{-2}$ day$^{-1}$), $G$ is soil heat flux density [MJ m$^{-2}$ day$^{-1}$], $T$ is mean air temperature at 2 m height (°C), $u_2$ is mean wind speed at 2 m height (m s$^{-1}$), $e_s$ is saturation vapour pressure (kPa), $e_a$ is actual vapour pressure (kPa), $e_s$-$e_a$ is saturation vapour pressure deficit (kPa), $\Delta$ is slope vapour pressure curve (kPa°C$^{-1}$), $\gamma$ is psychrometric constant (kPa °C$^{-1}$).

Hourly meteorological data needed as an input for calculation of hourly $ET_o$ using sASCE-PM equation was collected at the same site. sASCE-PM is given as:

$$ETo = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T + 273} u_2(e_s - e_a)}{(\Delta + \gamma(1 + C_d u_2)}$$

where *Cn* is numerator constant that changes with reference surface and calculation time step (900°C mm $s^3$ $Mg^{-1}$ $d^{-1}$ for 24 h time steps, and 37°C mm $s^3$ $Mg^{-1}$ $h^{-1}$ for hourly time steps for the grass-reference surface, *Cd* is denominator constant that changes with reference surface and calculation time step (0.34 s $m^{-1}$ for 24 h time steps, 0.24 s $m^{-1}$ for hourly time steps during daytime, and 0.96 s $m^{-1}$ for hourly night time for the grass-reference surface).

The sASCE-PM with *Cn* and *Cd* for daily time steps is exactly the same as the FAO-56-PM equation. However, for hourly time steps, the sASCE-PM uses a smaller value for surface resistance of vegetation per unit leaf area ($r_s$ (s $m^{-1}$)) during daytime (50 s $m^{-1}$) and a larger value for $r_s$ during night time (200 s $m^{-1}$). FAO 56-PM presumes constant $r_s$ of 70 s $m^{-1}$ during all periods (Allen et al., 1998). However, later, in 2005, FAO has recommended applying the FAO-56-PM for hourly or shorter periods using the same $r_s$ coefficients as for the ASCE-PM (Allen et al., 2006).

The calculation approach to calculate hourly $ET_o$ values, following the approach described in the ASCE-EWRI report, was developed by Snyder and Eching (2006). Required data for $ET_o$ calculations using sASCE-PM approach included data about site characteristics (latitude and elevation) and weather data, as hourly solar radiation ($R_s$) (MJ $m^{-2}$ $h^{-1}$), mean air temperature ($T$) (°C), mean wind speed ($u_2$) (m $s^{-1}$) and mean dew point temperature ($T_d$) (°C). $T_d$ was calculated using equation 3-11 in Allen et al. (1998). Actual vapour pressure ($e_a$ (kPa)) was calculated from mean saturation vapour pressure ($e_s$ (kPa) and relative humidity (*RH* (%)).

## 3 RESULTS WITH DISCUSSION

### 3.1 Comparison of FAO-56-PM (daily time step) and sASCE-PM (SOH and daily time steps) $ET_o$ calculations

Sum of hourly (for 24 h) $ET_o$ and daily $ET_o$ values calculated with sASCE PM equation were compared to daily $ET_o$ values computed with FAO-56-PM method. The results are presented in Figure 2. It has to be noted that sASCE-PM equation for short crop similar to grass was used to calculate the $ET_o$ values.

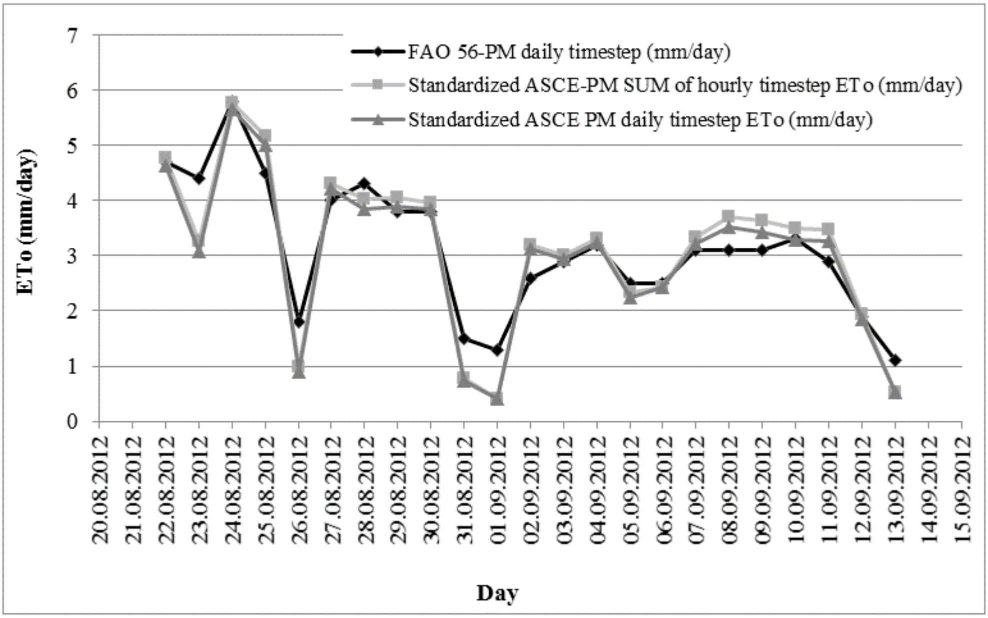


**Figure 2:** Comparison of reference evapotranspiration ($ET_o$ (mm/day)) values and sum of hourly and daily $ET_o$ (mm/day) values for short canopy obtained at agrometeorological station Celje-Medlog for period from 22. 8. 2012 to 13. 9. 2012
**Slika 2:** Primerjava dnevne referenčne evapotranspiracije ($ET_o$ (mm/dan)) in vsot urnih $ET_o$ (mm/dan) za kratko krošnjo, pridobljenih na agrometeorološki postaji Celje-Medlog za obdobje od 22. 8. 2012 do 13. 9. 2012

It can be visually observed from the Figure 2 that SOH and daily $ET_o$ values calculated with sASCE-PM equation fitted closely to daily $ET_o$ values calculated with FAO-56-PM equation. However, some discrepancy occurred for day 2 and for days, where $ET_o$ was generally low.

Table 2 shows calculated daily $ET_o$ and $ET_o$ differences between FAO-56-PM and sASCE-PM equations for location Celje-Medlog for period of 23 days (from 22$^{nd}$ of August 2012 to 13$^{th}$ of September 2012). Calculated ETo values using FAO-56-PM equation are presented as daily (24 h) time steps. ETo values calculated with sASCE-PM equation are presented as SOH time steps and, the same as with FAO-56-PM, as daily time steps.

**Table 2:** Daily and sum of hourly $ET_o$ and $ET_o$ differences for FAO 56-PM and sASCE-PM equations for location Celje-Medlog for period of from 22nd of August 2012 to 13th of September 2012.
**Preglednica 2:** Vsota urnih in dnevnih ETo vrednosti in njihove razlike za FAO 56-PM in sASCE-PM enačbi za lokacijo Celje-Medlog za obdobje od 22. 8. do 13. 9. 2012

| | A | B | C | | |
|---|---|---|---|---|---|
| Date | FAO 56-PM daily time step (mm/day) | Standardized ASCE PM daily time step (mm/day) | Standardized ASCE PM SOH time step (mm/day) | Difference (A-B) | Difference (A-C) |
| 22/08/2012 | 4.7 | 4.62 | 4.78 | 0.08 | -0.08 |
| 23/08/2012 | 4.4 | 3.08 | 3.26 | 1.32 | 1.14 |
| 24/08/2012 | 5.8 | 5.64 | 5.77 | 0.16 | 0.03 |
| 25/08/2012 | 4.5 | 5.00 | 5.17 | -0.50 | -0.67 |
| 26/08/2012 | 1.8 | 0.89 | 0.98 | 0.91 | 0.82 |
| 27/08/2012 | 4 | 4.20 | 4.3 | -0.20 | -0.30 |
| 28/08/2012 | 4.3 | 3.83 | 4.03 | 0.47 | 0.27 |
| 29/08/2012 | 3.8 | 3.90 | 4.06 | -0.10 | -0.26 |
| 30/08/2012 | 3.8 | 3.84 | 3.97 | -0.04 | -0.17 |
| 31/08/2012 | 1.5 | 0.73 | 0.78 | 0.77 | 0.72 |
| 01/09/2012 | 1.3 | 0.41 | 0.41 | 0.89 | 0.89 |
| 02/09/2012 | 2.6 | 3.13 | 3.19 | -0.53 | -0.59 |
| 03/09/2012 | 2.9 | 2.93 | 3.01 | -0.03 | -0.11 |
| 04/09/2012 | 3.2 | 3.24 | 3.31 | -0.04 | -0.11 |
| 05/09/2012 | 2.5 | 2.25 | 2.34 | 0.25 | 0.16 |
| 06/09/2012 | 2.5 | 2.42 | 2.42 | 0.08 | 0.08 |
| 07/09/2012 | 3.1 | 3.22 | 3.33 | -0.12 | -0.23 |
| 08/09/2012 | 3.1 | 3.51 | 3.71 | -0.41 | -0.61 |
| 09/09/2012 | 3.1 | 3.43 | 3.63 | -0.33 | -0.53 |
| 10/09/2012 | 3.3 | 3.29 | 3.5 | 0.01 | -0.20 |
| 11/09/2012 | 2.9 | 3.28 | 3.48 | -0.38 | -0.58 |
| 12/09/2012 | 1.9 | 1.84 | 1.95 | 0.06 | -0.05 |
| 13/09/2012 | 1.1 | 0.52 | 0.52 | 0.58 | 0.58 |
| Mean | 3.13 | 3.01 | 3.13 | | |

Comparisons made in Table 2 showed that the mean $ET_o$ value of 3.13 mm/day for investigated period was observed for FAO-56-PM and sASCE-PM SOH equations. Average $ET_o$ of 3.01 mm/day was observed for sASCE-PM equation for daily time step. When SOH and daily $ET_o$ values calculated with sASCE-PM equation were compared to FAO-56-PM equation, the biggest difference was observed for 23rd of August (1.32 and 1.14 mm/day) and the smallest one for 12th of August (0.06 and -0.05 mm/day). Sum of hourly ETo calculated with sASCE-PM equation were, when averaged, in better agreement with values observed with FAO-56-PM equation.

The paired *t*-test was used to compare the difference between each pair of results given by the two sASCE-PM $ET_o$ calculation methods. The null hypothesis was adopted saying that there is no significant difference in the mean $ET_o$ calculations given by all calculation methods. With other words, we have tested if the mean of the $ET_o$ differences differs significantly from zero. The results are presented in Table 3, showing that the $ET_o$ values calculated with sASCE-PM (daily and hourly) equation were not significantly different from the $ET_o$ values observed with FAO-56-PM equation. Therefore the null hypothesis was retained meaning that the applied methods of $ET_o$ calculations do not give significantly different values for the mean $ET_o$ value.

**Table 3:** Results of statistics of paired *t*-tests for the $ET_o$ calculated with sASCE-PM (daily) versus FAO-56 PM daily and sASCE-PM (SOH) versus FAO-56-PM daily values for selected period of 23 days
**Preglednica 3:** Statistični rezultati in parni *t*-test za ETo izračunano s sASCE-PM (dnevno) in FAO-56 PM dnevno metodo in vsoto urnih vrednosti, izračunanih s sASCE-PM proti FAO-56-PM dnevni metodi za preučevano obdobje 23 dni

| Location | Mean difference | | Standard deviation (SD) of the differences | | *t*-test (paired) computed* | | *t* critical |
|---|---|---|---|---|---|---|---|
| | ETo for FAO-56-PM - sASCE-PM (daily time step) | ETo for FAO-56-PM - sASCE-PM (SOH time step) | ETo for FAO-56-PM - sASCE-PM (daily time step) | ETo for FAO-56-PM - sASCE-PM (SOH time step) | ETo for FAO-56-PM - sASCE-PM (daily time step) | ETo for FAO-56-PM - sASCE-PM (SOH time step) | |
| Celje-Medlog | 0.13 | 0.01 | 0.48 | 0.5 | 1.26 | 0.08 | 2.07 |

*Degrees of freedom (n-1), P = 0.05 (5 % significance level)

It is important to mention that, when calculating SOH $ET_o$, some negative values were set to zero before summed over the 24-hours (SOH). This caused some minor differences in $ET_o$ daily calculations between sASCE-PM methods used in this research. Additional analysis showed that if negative hourly $ET_o$ values calculated with sASCE-PM method were left as negative, the SOH $ET_o$ values was identical to daily $ET_o$ values calculated with sASCE-PM. As mentioned in ASCE-EVRI (2005), the negative hourly $ET_o$ values may indicate the condensation of vapour during time of morning dew. However, the impact of SOH $ET_o$ values over daily periods using negative hourly values was, when compared to daily $ET_o$ values, less than 4 %.

## 4 CONCLUSIONS

In this paper the standardized sASCE-PM equation was evaluated against FAO-56-PM equation with a purpose to assess discrepancies between using a daily (24 h) time step equations (FAO-56-PM and sASCE-PM-daily) and sum of hourly (SOH) $ET_o$ (sASCE-PM-SOH) equation. Daily and hourly $ET_o$ computation time steps are in common use and it is important that hourly computations, when summed over a day (24 h) closely agree with daily time step calculations. Results revealed that SOH $ET_o$ values, calculated with sASCE-PM equation when compared to daily $ET_o$ values with FAO 56-PM and sASCE-PM, closely agree for most of investigated days. Comparisons showed that the mean $ET_o$ values for entire investigated period added up to 3.13 mm/day for FAO56-PM and sASCE-PM SOH equations and 3.01 mm/day for sASCE-PM daily time step equation. Also, the paired *t*-test showed that mean $ET_o$ value for entire period calculated with sASCE-PM (daily and hourly) equation were not significantly different ($P<0.05$) from the $ET_o$ values observed with FAO-56-PM equation. However, some discrepancy occurred for day 2 and for days, where $ET_o$ was generally low. The reason for these differences stays unknown. It has to be noted, however, that further research is needed to investigate the behaviour of those equations under given climate characteristics for longer time scales (e.g. 1 year or 1 growing season).

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