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Evaluation and validation of the ASCE standardized reference evapotranspiration equations for a subhumid site in northeastern Austria

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Abstract: Employing evapotranspiration models is a widely used method to estimate reference evapotranspiration (ET_{REF}) based on weather data. Evaluating such models considering site-specific boundary conditions is recommended to interpret ET_{REF}-calculations in a realistic and substantiated manner. Therefore, we evaluated the ASCE standardized ET_{REF}-equations at a subhumid site in northeastern Austria. We calculated ET_{REF}-values for hourly and daily time steps, whereof the former were processed to sum-of-hourly values. The obtained data were compared to each other and to ET-values measured by a weighing lysimeter under reference conditions. The resulting datasets covered daily data of the years 2004 to 2011.

Sum-of-hourly values correlated well ($r^2 = 0.978$) with daily values, but an RMSE of 0.27 mm specified the differences between the calculation procedures. Comparing the calculations to lysimeter measurements revealed overestimation of small ET_{REF}-values and underestimation of large values. The sum-of-hourly values outperformed the daily values, as r^2 of the former was slightly larger and RMSE was slightly smaller. Hence, sum-of-hourly computations delivered the best estimation of ET_{REF} for a single day. Seasonal effects were obvious, with computations and measurements being closest to each other in the summer months.

Keywords: Weighing lysimeter; Calculations; Hourly; Sum-of-hourly; Daily time steps.

INTRODUCTION

Evapotranspiration (ET) comprises processes of water vapor transport in the soil-plant-atmosphere system. These processes are driven by energy fluxes and vapor pressure deficit, and they are influenced by characteristics of soil and vegetation. Reference evapotranspiration (ET_{REF}) is defined as vaporization from a standardized surface – usually grass with specific attributes and not short of water – under the given meteorological conditions (Allen et al., 1998). ET-models incorporate relevant physical principles and specific parameters representing vegetation characteristics, and therefore enable calculating ET_{REF} based on atmospheric boundary conditions. A main advantage of ET-models is the availability and standardization of weather data as input (Allen et al., 2011). Other techniques such as weighing lysimeters allow measuring ET more accurately, but they require cost-intensive equipment. Therefore, weighing lysimeters are traditionally utilized to produce reference values for developing and validating ET-models (e.g., Aboukhaled et al., 1982; Doorenbos and Pruitt, 1977).

Several researchers tested the well-known equation after Penman and Monteith (PM) in different environments and declared it generally applicable (Allen et al., 1994; Jensen et al., 1990); hence, the Food and Agriculture Organization of the United Nations (FAO) recommended the PM-equation as standard procedure for computing ET_{REF} (FAO56; Allen et al., 1998). In this context, ET_{REF} serves as basis for calculating plant water requirements by means of standardized crop coefficients. Consequently, the PM-equation became widely accepted, and in 2005 the Environmental and Water Resources Institute of the American Society of Civil Engineers (ASCE) published a standardized equation with standardized calculation procedures (ASCE-EWRI, 2005). The declared intention was to "*bring commonality to the calculation of ET_{REF} and to provide a standardized basis for determining or transferring crop coefficients for agricultural and landscape use*" (ASCE-EWRI, 2005). For daily or longer time steps, the FAO56- and the ASCE-calculation procedures are identical (except for updated coefficients for calculating clear sky solar radiation in the ASCE version). The main update concerned the calculations of ET_{REF} on hourly time steps, which became more important due to the manifold application options and the increased availability of weather data in shorter than daily intervals (ASCE-EWRI, 2005). The central modification involved the modeling of the surface, which is assumed being short crop with an approximate height of 0.12 m (similar to clipped, cool-season grass). Its properties are expressed by the parameter of surface resistance (r_s), which is recommended to be for daily periods r_s = 70 s m^{-1}, and for hourly calculation r_s = 50 s m^{-1} during daytime and r_s = 200 s m^{-1} during nighttime (ASCE-EWRI, 2005).

Several studies thoroughly compared ASCE and FAO56 hourly and daily ET_{REF} equations among each other and with empirical equations (e.g., Gavilán et al., 2008; Irmak et al., 2005; Perera et al., 2015). The results indicated limitations of daily computation time steps as they disregard (irregular) diurnal changes in vegetation parameters (e.g., surface resistance, albedo) and weather data (e.g., wind speed, air temperature, vapor pressure deficit). Consequently, replacing daily calculations by sum-of-hourly (soh) calculations proved being advantageous when estimating ET_{REF} (Berengena and Gavilán, 2005; Gavilán, 2008; Irmak et al., 2005; Perera et al., 2015). ET_{REF} equations for daily and sum-of-hourly time steps were evaluated for different regions and climate zones throughout the world. Perera et al. (2015) related the deviations between daily ET_{REF}-values as calculated using the hourly and daily ASCE equations to Köppen climate zones of Australia. In doing so, the authors report good agreement in general, but also an overestimation of daily ET_{REF} based on the hourly equation. The overestimation was larger in temperate climates compared to arid and tropical conditions. In this regard, Perera et al. (2015) also reported a notable seasonality as the relation between hourly and daily estimates changed with time of year.

Other studies compared ET_{REF} estimates with lysimeter measurements (e.g., Allen et al., 1994; Berengena and Gavilan, 2005; Garcia et al., 2004; Gavilan et al., 2007; Howell et al., 2000; Nolz et al., 2016; Perez et al., 2006; Yoder et al., 2005). An overall conclusion is that calculated ET_{REF} is generally larger than measured ET at small rates and vice versa. Furthermore, deviations seem to be more pronounced under semiarid and windy conditions with a high evaporative demand. Such systematic inconsistencies are usually attributed to advection of sensible heat, estimated input data (e.g., net radiation, soil heat flux) or surface resistance parameters. However, identifying the cause is extremely challenging as several interacting factors could play a role.

The overall objective of this study was to evaluate and validate the ASCE standardized reference evapotranspiration equations for a subhumid site in northeastern Austria. In this regard, the following specific objectives were addressed:

(i) Identifying differences associated with using hourly and daily time steps of the ASCE calculation procedure;
(ii) Evaluating computed ET_{REF} in relation to ET-values measured by a precision weighing lysimeter;
(iii) Evaluating deviations between calculated and measured ET_{REF} considering antecedent rainfall and irrigation;
(iv) Evaluating deviations between calculated and measured ET_{REF} with respect to seasonal effects.

The study was based on a comprehensive dataset covering several vegetation periods. Due to a specific data processing technique (Nolz et al., 2013a, b) the data contained also ET of rainy days (Nolz et al., 2014). This can be regarded as especially beneficial as many of the above-mentioned studies refer to filtered datasets only.

MATERIALS AND METHODS

The utilized dataset included meteorological data for computing reference evapotranspiration and lysimeter data from 2004 to 2011. All data were measured at an experimental site in Groß-Enzersdorf, in northeastern Austria (48°12'N, 16°34'E; 157 m). The measurement area of approximately 50×50 m was kept with short grass (except for a second lysimeter that was planted with crops alternating year by year). Agricultural fields and some small buildings surrounded the grassland. The adjacent area represents one of the major crop production areas, but also one of the driest regions of Austria. In the period 1981–2010, mean annual precipitation and temperature were 550 mm and 10.7°C, respectively; the climate can be characterized as subhumid (according to Köppen: Cfb – temperate climate without dry season and warm summer).

Meteorological data

Meteorological data were provided by the Central Institute for Meteorology and Geodynamics, Austria (ZAMG). The dataset included hourly data of solar radiation R_s (MJ·m^{-2}·h^{-1}), air temperature T (°C), relative humidity RH (%), atmospheric pressure p (kPa), and wind velocity in 10 m height U_{10} (m·s^{-1}). Atmospheric pressure records were available only from 2006 to 2011. Daily solar radiation was calculated as hourly sums. According to ZAMG-standards, daily values for relative humidity, air pressure, and wind velocity were derived as average of the respective measurement at 7 a.m., 2 p.m., and 7 p.m. Daily temperature represents the mean of daily maximum T_{max} and minimum T_{min}. Precipitation per day is the sum of hourly records from 7 a.m. to 7 a.m. of the following day.

Reference evapotranspiration

Reference evapotranspiration was calculated for hourly and daily time steps according to the standardized ASCE Penman-Monteith equation (Eq. 1) (ASCE-EWRI, 2005).

$$ET_{\text{ASCE-PM}} = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{C_n}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d U_2)} \tag{1}$$

In this article, calculated daily evapotranspiration for a short reference crop (similar to grass with an approximate height of 0.12 m) is referred to as $ET_{\text{ASCE-PM, d}}$ (mm·d^{-1}). In this case, the numerator and denominator constant was $C_n = 900$ and $C_d = 0.34$, respectively. For the hourly computations the constants were $C_n = 37$ and $C_d = 0.24$ during daytime (when net radiation $R_n > 0$), and $C_d = 0.96$ during nighttime ($R_n < 0$). Sum-of-hourly (soh) evapotranspiration was computed by summing the hourly values; it is denoted as $ET_{\text{ASCE-PM, soh}}$ (mm·d^{-1}). All inter-calculations were done according to ASCE-EWRI (2005). The slope of saturation vapor pressure-temperature curve Δ (kPa·°C^{-1}) was calculated as a function of mean air temperature T (°C) in the respective period. Net radiation at vegetation surface R_n (MJ·m^{-2}·d^{-1} or MJ·m^{-2}·h^{-1}) is defined as $R_n = R_{ns} – R_{nl}$, where R_{ns} is net solar radiation and R_{nl} is net long-wave radiation. R_{ns} was computed as measured solar radiation R_s minus reflected fraction $\alpha \cdot R_s$ (albedo $\alpha = 0.23$). R_{nl} was calculated as a function of the Stefan-Boltzmann constant (4.901·10^{-9} MJ·K^{-4}·m^{-1}·d^{-1} for daily and 2.042·10^{10} MJ·K^{-4}·m^{-1}·h^{-1} for hourly time steps), actual vapor pressure e_a (kPa), mean absolute temperature T_K (K) in the respective time period, and a dimensionless cloudiness function f_{cd}. The latter is a function of relative solar radiation $R_s \cdot R_{so}^{-1}$, where R_{so} represents calculated clear-sky radiation (MJ·m^{-2}·d^{-1} or MJ·m^{-2}·h^{-1}). R_{so} was computed as $R_{so} = K_{ab} \cdot R_a$, with $K_{ab} = a + b$ with the site-specific factors $a = 0.21$ and $b = 0.54$ (Trnka et al., 2005), and extraterrestrial radiation R_a depending on day of year, time of day, and latitude.

Soil heat flux density at the soil surface G (MJ·m^{-2}·d^{-1} or MJ·m^{-2}·h^{-1}) was set zero for daily time steps, and for hourly time steps $0.1 \cdot R_n$ and $0.5 \cdot R_n$ at daytime and nighttime, respectively (ASCE-EWRI, 2005). The psychrometric constant γ (kPa·°C^{-1}) is a function of atmospheric pressure p. The missing p-data of the years 2004 and 2005 were compensated by including data from a weather station at a comparable site, only 5 km apart and at the same elevation. T represents the mean air temperature at 1.5 to 2.5 m height (°C). Mean wind velocity at 2 m height U_2 (m·s^{-2}) was calculated from measured U_{10} by means of the standard wind profile relationship according to ASCE-EWRI (2005). Saturation vapor pressure e_s (kPa) was calculated as a function of daily maximum and minimum temperature (T_{max}, T_{min}) and measured hourly T, respectively. Actual vapor pressure e_a (kPa) was computed from mean RH and T in the respective daily or hourly time interval. Alternatively, hourly e_a (2004–2011) was averaged to daily values representing the most preferred method according to ASCE-EWRI (2005).

Lysimeter evapotranspiration

Evapotranspiration of grass canopy was measured under reference conditions by means of a weighing lysimeter. The cylindrical lysimeter container had an inner diameter of 1.9 m (surface area = 2.85 m^2) and a hemispherical bottom with a free draining outlet at 2.5 m depth. Soil was sandy loam soil (0–140 cm) over gravel (140–250 cm). In the course of the study period (2004–2011), top soil was cultivated and grass was renewed early in 2004 and 2007. Grass on and beside the lysimeter was regularly clipped and irrigated, and temporarily fertilized and cleared from weed.

Lysimeter evapotranspiration (ET_{LYS}) was determined by considering changes of soil water within the lysimeter (ΔW) and fluxes across its lower and upper boundary.

The nominal lysimeter weight was quantified by means of a weighing facility, which comprised a mechanical system to transform the weight and an electronic load cell with a measuring accuracy of ±0.2 kg (Nolz et al., 2013a). The analog output signal was amplified, converted to digital units, averaged and stored on a local server. Logging intervals were 15 minutes from 2004 to 2009 and 10 minutes from 2009 to 2011. The logged values were converted into physical quantities (with a dimension of mass) by means of calibration factors. Dividing by the lysimeter surface area and the density of water resulted in nominal values of soil water content (W_{LYS}) with a dimension of length. It has to be noted that the total mass of the lysimeter (and the solid soil) is unknown, so the values must not be interpreted as absolute water content.

Drainage water was quantified by means of a tipping bucket at the bottom outlet of the lysimeter. Tipping and weighing data were logged at the same time. Counts of tipping were converted into outflow data using a calibration factor and divided by the lysimeter surface area to obtain drainage water (W_{DRAIN}) with a dimension of length (Nolz et al., 2013b).

Soil and drainage water were combined to a nominal time series (W_{LYS} + W_{DRAIN}). The time series was processed by means of smoothing functions to facilitate further data interpretation (Nolz et al., 2013b, 2014). Changes between two values of the smoothed time series were attributed to fluxes across the upper boundary of the lysimeter such as evapotranspiration (ET), precipitation (P), and irrigation (I) (Eq. 2).

$$\Delta(W_{LYS} + W_{DRAIN}) = \Delta P + \Delta I - \Delta ET_{LYS} \quad (2)$$

W_{LYS} = soil water content; W_{DRAIN} = drainage water; P = precipitation; I = irrigation; ET_{LYS} = evapotranspiration; all components have the dimension ($L \cdot T^{-1}$).

Consequently, positive values of $\Delta(W_{LYS} + W_{DRAIN})$ – referring to a time interval of 10 or 15 minutes – were attributed to precipitation and irrigation, of which the irrigation events could be identified based on manual notes. Accordingly, negative values of $\Delta(W_{LYS} + W_{DRAIN})$ were considered as lysimeter ET at reference conditions (ET_{LYS}). On this basis, ET_{LYS} was calculated for daily time steps (ET_{LYS} / $mm \cdot d^{-1}$), with each day lasting from 7 a.m. to 7 a.m. of the following day.

Comparison and statistical evaluation

The scatter diagrams in the results section illustrate the relation between one dataset as independent variable x and another dataset as dependent variable y (Table 1). The comparisons were evaluated by means of linear regression of the form $y = a \cdot x + b$ (a = slope, b = intercept, and r^2 = coefficient of determination) and simple error analysis using root mean square error RMSE ($mm \cdot d^{-1}$) (Eq. 3).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y-x)^2} \quad (3)$$

RESULTS AND DISCUSSION

Identifying differences associated with using hourly and daily time steps of the ASCE calculation procedure

For comparing daily ($ET_{ASCE\text{-}PM,\,d}$) with sum-of-hourly reference evapotranspiration ($ET_{ASCE\text{-}PM,\,soh}$), n = 2922 data pairs were computed based on the weather data of 2004 to 2011 (Fig. 1). The correlation between the datasets was very good (r^2 = 0.978), but the RMSE = 0.266 $mm \cdot d^{-1}$ indicated noticeable differences between single values of the datasets. Comparable characteristics can be found in literature: Gavilan et al. (2008) reported coefficients of correlation r^2 = 0.986 and 0.973, and RMSE = 0.24 and 0.36 $mm \cdot d^{-1}$ (n = 1090) for two semiarid sites in Spain. Irmak et al. (2005) tested both calculation methods for nine reference sites in the United States, resulting in r^2 values between 0.947 and 0.987, and RMSE between 0.25 and 0.56 $mm \cdot d^{-1}$ (n = 366–1826). Perera et al. (2015) presented average values of r^2 = 0.981 and RMSE = 0.281 $mm \cdot d^{-1}$ for 40 Australian sites; however, the mean slope (a = 0.948) and intercept (b = 0.195) indicated considerable deviation from the 1:1 line. Differences between daily and hourly computations are assumed to occur due to averaging of weather data (for the daily values) and due to different surface resistance parameters for daily and hourly calculation steps. In general, both methods have their advantages. Daily calculations, above all, are easier to handle. On the other hand, hourly calculations allow estimating ET_{REF} (and consequently plant water uptake) during the course of day and night, including also dew formation (e.g. Nolz et al., 2014). For longer periods, both methods are expected to deliver similar results. However, the annual sums of the hourly calculation steps were larger than the sums of daily values (Table 2). A similar overestimation of hourly calculations was reported by Perera et al. (2015). When looking more closely to the linear trend and the 1:1 line in Fig. 1, it appears that $ET_{ASCE\text{-}PM,\,soh}$ was slightly larger at moderate ET-rates of around 4 $mm \cdot h^{-1}$. Although these deviations are small, they seem to add up to larger differences in the annual sums (Table 2).

Evaluating computed ET_{REF} in relation to ET-values measured by a precision weighing lysimeter

Evapotranspiration data from the reference lysimeter (ET_{LYS}) include the vegetative periods of grass between 2004 and 2011. Some data were missing because of system failures or excluded because of adverse conditions such as snow and frost during winter. Thus, n = 2185 daily values (of max. n = 2920) remained for evaluation, which is a considerable number compared to other studies. Daily computations ($ET_{ASCE\text{-}PM,\,d}$) correlated well with daily measurements (ET_{LYS}): r^2 was 0.934 and

Table 1. Comparison of datasets from calculations (calc.) and lysimeter measurements (meas.).

	Independent variable x	Dependent variable y
Daily calc. vs. sum-of-hourly calc.	$ET_{ASCE\text{-}PM,\,d}$ / $mm \cdot d^{-1}$	$ET_{ASCE\text{-}PM,\,soh}$ / $mm \cdot d^{-1}$
Daily calc. vs. daily meas.	ET_{LYS} / $mm \cdot d^{-1}$	$ET_{ASCE\text{-}PM,\,d}$ / $mm \cdot d^{-1}$
Daily calc. vs. sum-of-hourly meas.	ET_{LYS} / $mm \cdot d^{-1}$	$ET_{ASCE\text{-}PM,\,soh}$ / $mm \cdot d^{-1}$
Hourly calc. vs. hourly meas.	$ET_{LYS,\,h}$ / $mm \cdot h^{-1}$	$ET_{ASCE\text{-}PM,\,h}$ / $mm \cdot h^{-1}$

Table 2. Overview on reference evapotranspiration, air temperature, and precipitation during the studied years.

	Annual sum $ET_{ASCE\text{-}PM,\,d}$ mm	Annual sum $ET_{ASCE\text{-}PM,\,soh}$ mm	Annual mean temperature °C	Annual mean precipitation mm
2004	790	812	10.6	540
2005	792	810	10.3	520
2006	822	845	10.9	520
2007	908	920	11.9	770
2008	836	857	11.7	610
2009	835	854	11.4	560
2010	760	774	10.1	690
2011	846	863	11.3	400

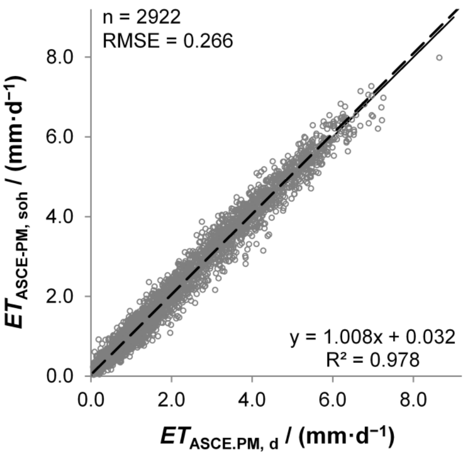

Fig. 1. Calculated sum-of-hourly ($ET_{ASCE\text{-}PM,\,soh}$) versus daily ($ET_{ASCE\text{-}PM,\,d}$) reference evapotranspiration.

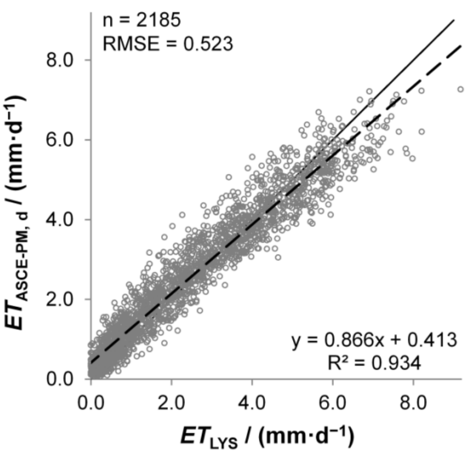

Fig. 2. Reference ET computed for daily time steps ($ET_{ASCE\text{-}PM,\,d}$) versus lysimeter measurements under reference conditions (ET_{LYS}).

RMSE was 0.523 mm·d^{-1} (Fig. 2). The latter indicates the average accuracy that can be expected for any estimated value. Unfortunately, we could not find a comparable lysimeter study stating explicitly the same statistical parameters r^2 and RMSE in literature. A comparable study presenting the standard error of the estimate (SEE, instead of RMSE) was published by Yoder et al. (2005). They related FAO56-ET to lysimeter ET (n = 296, data from 5 years), resulting in correlation parameters a = 0.755 and b = 0.709, a coefficient of correlation r^2 = 0.909, and an SEE = 0.31 mm·d^{-1}. The linear trend line in Fig. 2 illustrates an overestimation of $ET_{ASCE\text{-}PM,\,d}$ at small values and an underestimation at larger values. This is in accordance with results of many other studies (e.g., Allen et al., 1994; Berengena and Gavilan, 2005; Garcia et al., 2004; Gavilan et al. 2007; Howell et al., 2000; Perez et al. 2006; Yoder et al., 2005).

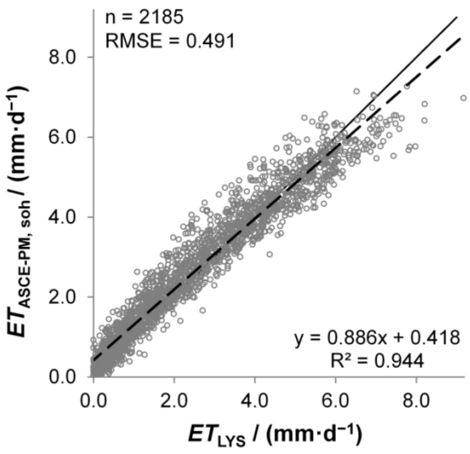

Fig. 3. Reference ET computed as sum-of-hourly values ($ET_{ASCE\text{-}PM,\,soh}$) versus lysimeter measurements under reference conditions (ET_{LYS}).

The correlation between sum-of-hourly data ($ET_{ASCE\text{-}PM,\,soh}$) and ET_{LYS} was slightly better than that of the daily time steps: r^2 was 0.944 and RMSE was 0.491 mm·d^{-1} (Fig. 3). As the latter represents the average deviation of a single value, sum-of-hourly calculations can be regarded marginally more accurate than the daily calculations with an RMSE = 0.523 mm·d^{-1} (Fig. 2). By applying the same method, Gavilan et al. (2007) achieved a correlation with slope a = 0.82 and intercept b = 1.12; r^2 was 0.92 and RMSE was 0.45 mm·d^{-1} (only small dataset of n = 81). Thus, a value of 0.5 mm·d^{-1} is supposed to represent the expected accuracy when estimating ET_{REF}. Under the given environmental conditions, it is therefore recommended to access hourly weather data and calculate sum-of-hourly values to obtain as accurate as possible estimations of daily of ET_{REF}.

Evaluating deviations between calculated and measured ET_{REF} considering antecedent rainfall and irrigation

Despite the better performance, the course of the trend line in Fig. 3 reflects the same tendency as presented for daily calculations. Above all, it indicates a considerable underestimation of $ET_{ASCE\text{-}PM}$ at larger values. Some of these values could be attributed to days at which the lysimeter was irrigated. In such cases, the wetting of the surface might have led to increased evaporation rates at the lysimeter, which are beyond the definition of reference evapotranspiration. Furthermore, antecedent rainfall could have had an influence. To examine if these limitations of lysimeter measurements affected the model validation in general, the available dataset was filtered: Fig. 4 illustrates data pairs of days without rain and irrigation (n = 1153). In this case, potential disturbing impacts from unintended evaporation were avoided. Compared to Fig. 3, correlation was similar and RMSE was slightly larger (but still smaller than in Fig. 2).

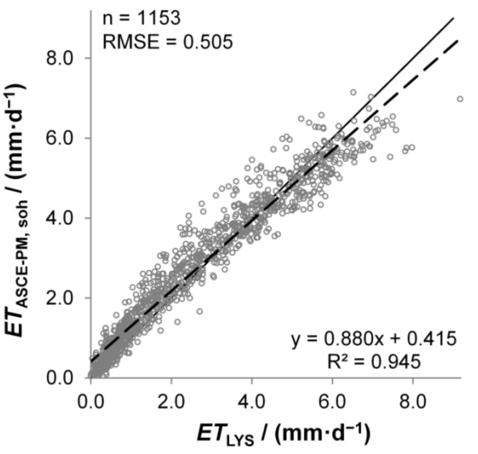

Fig. 4. Calculated ($ET_{\text{ASCE-PM, soh}}$) versus measured (ET_{LYS}) ET at days without rain and irrigation to avoid disturbing influences from unintended evaporation.

Hence, it can be concluded that antecedent rainfall and irrigation events did not bias the presented *ET* measurements.

As a further filtering approach, only days up to three days after rainfall and irrigation were considered. This was done to guarantee satisfactory soil moisture distribution at the study site and to reduce advection of sensible heat from the surroundings. In this context, it has to be mentioned that advection of sensible heat at this study site is supposed to have minor impact according to Nolz et al. (2016). The final (reduced) dataset contained $n = 740$ data pairs, which is still comparable to sample sizes of other *ET* studies (e.g. Gavilan et al., 2008; Irmak et al., 2005). The resulting correlation (Fig. 5a) and the parameters r^2 and RMSE were similar to Fig. 3. From this can be concluded that the dataset and the results are consistent and not influenced by systematic measurement errors.

Nevertheless, it seems that the linear trend in Fig. 5a does not represent the best possible correlation. In fact, r^2 could be increased by fitting a polynomial trend (Fig. 5b). The latter indicates good accordance at small *ET*-rates, while the calculated values seem to exceed the measurements at moderate rates, and underestimate measurements at large rates. The same characteristic can be deduced from Fig. 2 and Fig. 3.

Hourly calculated and measured data pairs were linearly correlated with an r^2 of 0.922 (Fig. 6), which is comparable to the correlation of daily data (Fig. 2). This indicates that there are no systematic errors between hourly and daily calculation steps.

However, deviations between single values – as reflected by the scatter-plot in Fig. 6 – reveal a larger uncertainty when estimating hourly ET. The respective RMSE was 0.044 mm·h^{-1}. It is obvious that at *ET*-rates larger than 0.6 mm·h^{-1} lysimeter measurements were considerably larger than the calculated values; on the other hand, measurements between 0.2 and

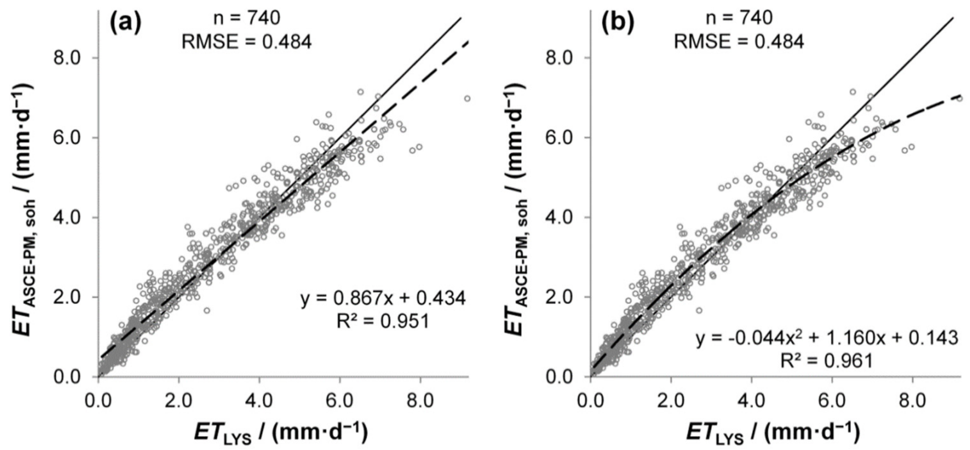

Fig. 5. Calculated ($ET_{\text{ASCE-PM, soh}}$) versus measured (ET_{LYS}) ET at days without rain and irrigation, including only up to three days after rainfall to guarantee homogenous soil moisture distribution at the study site; (a) with linear trend, (b) with polynomial trend.

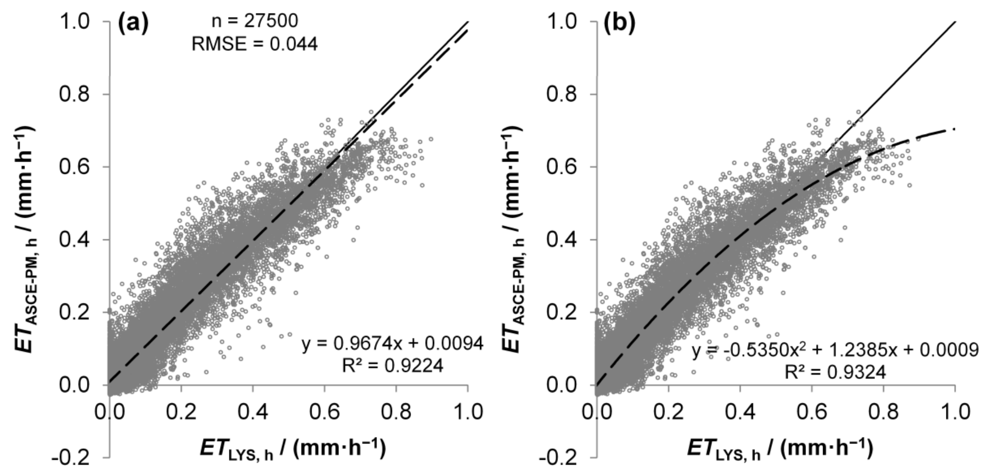

Fig. 6. Hourly calculated ($ET_{\text{ASCE-PM, h}}$) versus hourly measured ($ET_{\text{LYS, h}}$) ET of a 4-year-period (2008 to 2011); (a) with linear trend, (b) with polynomial trend.

$0.4\ mm \cdot h^{-1}$ were overestimated by calculations. Similar to the daily values, this caused a slight shift of the linear trend illustrated Fig. 6a, and a considerable curvature of the polynomial trend in Fig. 6b. Further interpretations are beyond the scope of this article, but examining this phenomenon in future studies is highly recommended.

Evaluating deviations between daily calculated and measured ET_{REF} with respect to seasonal effects

To be able to evaluate whether the nonlinear relationship arose due to seasonal effects, the scatter plots were separated into the four seasons. In Fig. 7, spring is represented by the months March, April, and May (MAM, Fig. 7a), summer covers June, July, and August (JJA, Fig. 7b), autumn covers September, October, and November (SON, Fig. 7c), and winter covers December, January, and February (DJF, Fig. 7d). It appears that in autumn (Fig. 7c) the trend line is close to the 1:1-line, indicating a very good accordance between measurements and calculations. For the other seasons (Fig. 7a, c, and d), small ET_{REF}-values are overestimated and vice versa – as it is generally the case. Consequently, no distinct seasonal effects can be deduced from the data shown in Fig. 7 compared to the entire data set as shown in Fig. 3.

Furthermore, ratios were calculated of ($ET_{ASCE\text{-}PM,\ soh}$ / $ET_{ASCE\text{-}PM,\ d}$) (Fig. 8a), ($ET_{ASCE\text{-}PM,\ soh}$ / ET_{LYS}) (Fig. 8b), and ($ET_{ASCE\text{-}PM,\ d}$ / ET_{LYS}) (Fig. 8c). This was done to be able to evaluate the average difference between the data sets. Fig. 8 contains the ratios of the entire data set (All) as well as single seasons (spring-months – MAM, summer-months – JJA, autumn-months – SON, and winter-months – DJF). The ratios are illustrated as box plots with the median as a dash. A value close to one represents a good accordance of the data sets, while deviations reveal underestimation or overestimation of values. The boxes in Fig. 8 represent the 25 to 75% quantiles, the whiskers indicate the 5 and 95% percentile, and outliers are depicted as crosses. It has to be noted that such ratios strongly depend on the absolute values of *ET*, which is the reason why large values (outliers) must be accepted in this way of representing. Mean ratios of computed sum-of-hourly values to daily values were 1.00 for the summer months, indicating a very good match on average (Fig. 8a, and Table 3). However, sum-of-hourly values were 5% larger than daily values when considering the entire year. These results are similar to the ratios reported by Perera et al. (2015) for stations with comparable climatic conditions. Calculated values were generally larger than measured ones, as demonstrated by ratios larger than one in Fig. 8b, c, and Table 3. Seasonal differences were obvious, although the ratios for the winter months (DJF) must not be over-interpreted as the grass might have been in dormancy. Overall, the results clearly indicate the best performance of the *ET*-equations in summer (mean close to one, narrow quantiles). Furthermore, calculations generally overestimated measured values as indicated by values larger 1.00 in Table 3. In March, April, May (MAM) and September, October, November (SON), daily calculations outperformed sum-of-hourly calculations. On the other hand, standard deviations of the sum-of-hourly calculations were smaller, which is in accordance with the smaller RMSE value shown in Fig. 3. The overall conclusion is that sum-of-hourly calculations are expected to deliver

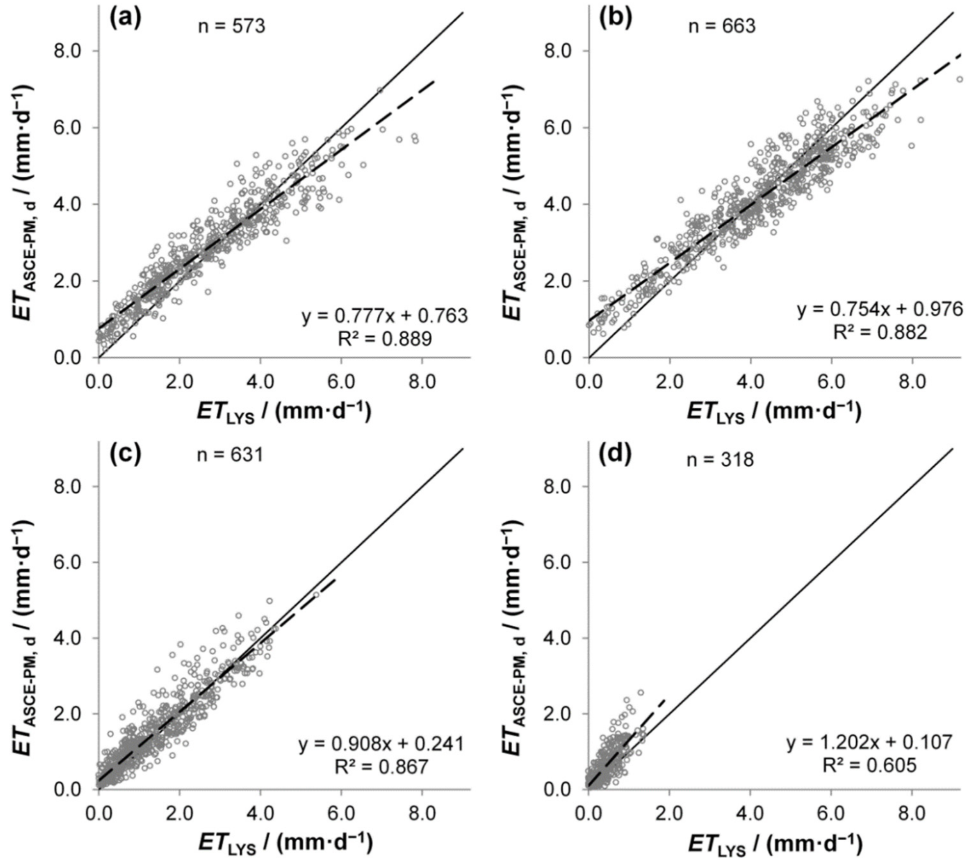

Fig. 7. Evaluation of computed versus measured data with respect to seasonal differences: correlations of spring- (a) and summer-data (b) are similar to the correlation of the entire data set (Fig. 3); autumn-data (c) are more close to the 1:1-line; winter-data (d) do not allow a consistent conclusion based on the correlation.

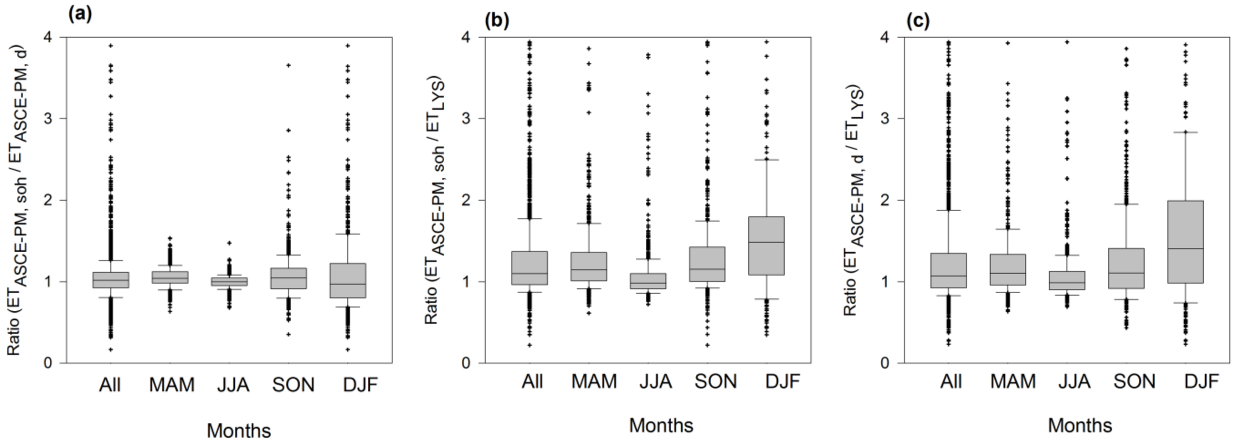

Fig. 8. Ratios of (a) calculated (b), (c) calculated and measured ET values illustrating general (All) and seasonal (MAM, JJA, SON, DJF) differences as deviations from a value of one.

Table 3. Mean values and standard deviations (SD) of the ratios illustrated in Fig. 8.

	Ratio ($ET_{\mathrm{ASCE\text{-}PM,\,soh}}$ / $ET_{\mathrm{ASCE\text{-}PM,\,d}}$)					Ratio ($ET_{\mathrm{ASCE\text{-}PM,\,soh}}$ / ET_{LYS})					Ratio ($ET_{\mathrm{ASCE\text{-}PM,\,d}}$ / ET_{LYS})				
Months	All	MAM	JJA	SON	DJF	All	MAM	JJA	SON	DJF	All	MAM	JJA	SON	DJF
Mean	1.05	1.05	1.00	1.07	1.10	1.28	1.27	1.08	1.33	1.66	1.28	1.24	1.09	1.31	1.69
SD	0.32	0.12	0.08	0.27	0.56	0.66	0.56	0.40	0.65	1.03	0.75	0.59	0.46	0.74	1.20

values that are more accurate for a single day. Seasonal effects are observable, but further studies are recommended to determine the underlying causes.

CONCLUSIONS

The ASCE standardized ET_{REF}-equations were evaluated at a subhumid site in northeastern Austria. ET_{REF}-values were calculated for hourly and daily time steps, whereof the former were processed to sum-of-hourly values. (i) Identifying differences associated with using hourly and daily time steps: Sum-of-hourly values correlated well (r^2 = 0.978) with values computed on daily time steps, but an RMSE of 0.27 mm specified differences (uncertainties) between the calculation procedures. (ii) Evaluating computed ET_{REF} in relation to ET-values measured by a precision weighing lysimeter: Comparing the calculations to lysimeter measurements confirmed overestimation of small ET_{REF}-values and underestimation of large values as known from other studies. Based on the scatter plots, the sum-of-hourly computations outperformed the daily computations, as r^2 of the former was slightly larger and RMSE was slightly smaller. (iii) Evaluating deviations between calculated and measured ET_{REF} considering antecedent rainfall and irrigation: It was shown that the results were not distorted by antecedent rainfall, irrigation, or insufficient soil water conditions. (iv) Evaluating deviations between calculated and measured ET_{REF} with respect to seasonal effects: Seasonal effects were obvious – with computations and measurements being closest to each other in the summer months. In general, sum-of-hourly computations delivered the best estimation of ET_{REF} for a single day. Daily calculation steps, of course, have the advantage of being simpler. Hence, both calculation methods have their advantages under the given environmental conditions. On the other hand, neither of them results in a fully satisfying estimation of ET_{REF}, so further studies are recommended in this regard.

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REFERENCES

Aboukhaled, A., Alfaro, A., Smith, M., 1982. Lysimeters. In: Irrigation and Drainage Paper 39, FAO, Rome (Italy), 73 p.

Allen, R.G., Smith, M., Perrier, A., Pereira, L.S., 1994. An update for the calculation of reference evapotranspiration. ICID (International Commission on Irrigation and Drainage) Bulletin, 43, 2, 35–92.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: guidelines for computing crop water requirements. In: Irrigation and drainage paper 56. Food and Agriculture Organization of the United Nations, Rome.

Allen, R.G., Pereira, L.S., Howell, T.A., Jensen, M.E., 2011. Evapotranspiration information reporting: I. Factors governing measurement accuracy. Agricultural Water Management, 98, 899–920.

ASCE-EWRI, 2005. The ASCE standardized reference evapotranspiration equation. In: Allen, R.G.,Walter, I.A., Elliott, R., Howell, T., Itenfisu, D., Jensen, M. (Eds.): ASCE-EWRI Task committee report. American Society of Civil Engineers, Reston, VA, 171 p.

Berengena, J., Gavilán, P., 2005. Reference evapotranspiration estimation in a highly advective semiarid environment. J. Irrig. Drain. Eng., 131, 2,147–163.

Doorenbos, J., Pruitt, W.O., 1977. Guidelines for predicting crop water requirements. In: Irrigation and drainage paper 24. Food and Agriculture Organization of the United Nations, Rome, 175 p.

Garcia, M., Raes, D., Allen, R., Herbas, C., 2004. Dynamics of reference evapotranspiration in the Bolivian highlands (Altiplano). Agric. For. Meteorol., 125, 1–2, 67–82.

Gavilan, P., Berengena, J., Allen, R.G., 2007. Measuring versus estimating net radiation and soil heat flux: Impact on Penman–Monteith reference ET estimates in semiarid regions. Agric. Water Manage., 89, 275–286.

Gavilán, P., Estévez J., Berengena J., 2008. Comparison of standardized reference evapotranspiration equations in southern Spain. J. Irrig. Drain. Eng., 134, 1–12.

Howell, T.A., Evett, S.R., Schneider, A.D., Dusek, D.A., Copeland, K.S., 2000. Irrigated fescue grass ET compared with calculated reference grass ET. In: Proceedings of 4th National Irrigation Symposium, ASAE, Phoenix, AZ, pp. 228–242.

Irmak, S., Howell, T.A., Allen, R.G., Payero, J.O., Martin, D.L., 2005. Standardized ASCE Penman-Monteith: impact of sum-of-hourly vs. 24-hour timestep computations at reference weather station sites. T. ASEA, 48, 1063–1077.

Jensen, M.E., Burman, R.D., Allen, R.G., 1990. Evapotranspiration and irrigation water requirements. ASCE Manuals and Reports on Engineering Practice, No. 70. American Society of Civil Engineers, New York.

Nolz, R., Kammerer, G., Cepuder, P., 2013a. Interpretation of lysimeter weighing data affected by wind. J. Plant Nutr. Soil Sci., 176, 200–208.

Nolz, R., Kammerer, G., Cepuder, P., 2013b. Improving interpretation of lysimeter weighing data. Die Bodenkultur: J. Land Manage. Food Environ., 64, 27–35.

Nolz, R., Cepuder, P., Kammerer, G., 2014. Determining soil water-balance components using an irrigated grass lysimeter in NE Austria. J. Plant Nutr. Soil Sci., 177, 237–244.

Nolz, R., Cepuder, P., Eitzinger, J., 2016. Comparison of lysimeter based and calculated ASCE reference evapotranspiration in a subhumid climate. Theor. Appl. Climatol., 124, 315–324.

Perez, L., Castellvi, F., Martínez-Cob, A., Villalobos, F.J., 2006. A simple parameterization of bulk canopy resistance from climatic variables for estimating hourly evapotranspiration. Hydrol. Process., 20, 515–532.

Perera, K.C., Western, A.W., Nawarathna, B., George, B., 2015. Comparison of hourly and daily reference crop evapotranspiration equations across seasons and climate zones in Australia. Agric. Water Manage., 148, 84–96.

Trnka, M., Žalud, Z., Eitzinger, J., Dubrovský, M., 2005. Global solar radiation in Central European lowlands estimated by various empirical formulae. Agric. For. Meteorol., 131, 54–76.

Yoder, R.E., Odhiambo, L.O., Wright, W.C., 2005. Evaluation of methods for estimating daily reference crop evapotranspiration at a site in the humid Southeast United States. Appl. Eng. Agric., 21, 2, 197–202.

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