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Validation of diurnal soil moisture dynamic-based evapotranspiration estimation methods

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Abstract—Evapotranspiration (*ET*) is one of the most important elements of water balance. Despite its importance, exact determination for a mosaic surface cover is very limited; therefore, there is a demand for relatively simple and cheap methods of determination that work on a small spatial scale.

Water uptake of forest vegetation in groundwater discharge areas generally has a strong influence on the water resources induced diurnal signal in soil moisture, and in the water table. Diurnal methods in a shallow groundwater environment are widely used nowadays for *ET* estimation.

By modifying the well-known *White* (1932) method and adapting to soil moisture data, a new technique was developed to calculate *ET* from soil moisture readings, eliminating the need of specific yield (a weakest point of the groundwater signal based methods). The new method was validated using hydro-meteorological data of the Hidegvíz Valley experimental catchment located in the Sopron Hills at the western border of Hungary.

The 30-min *ET* rates of the proposed method lag 30-60 minutes behind those of the reference Penman–Monteith method, but otherwise the two estimates compare favorably.

On a daily basis, the newly derived *ET* rates are very close to PM estimates, but on average, they are 38% higher than the ones obtainable with the original White method. Comparing the *ET* rates of the proposed method with traditional *ET* estimates from soil moisture, a significant difference can be ascertained.

The proposed method has potential benefits in groundwater discharge areas, especially in light of the changing climate with its warmer and drier growing seasons, that will likely result in limited water resources.

Key-words: evapotranspiration, soil moisture, diurnal signal, discharge areas, forest

1. Introduction

After precipitation, evapotranspiration (*ET*) is the second largest element of the water balance globally. In Hungary (on the border of the sub-humid and semi-arid climate conditions), *ET* makes up about 90% of the precipitation on the catchments scale in long-term average. Despite the importance of *ET*, it is determined mostly as a lumped residual flux from a long-term water balance equation of a catchment. This method has some drawbacks. It cannot give spatially distributed information within a catchment and is limited in terms of time resolution, because it only considers long-term average values. Using data of a local weather station for *ET* calculation, we can acquire more detailed time information, but the space domain limits of the approach remain. Nowadays, the scintillometer technique and remote sensing based information has started to resolve the problem of spatial distribution at a larger scale, but the application of these methods are still limited with highly heterogeneous, mosaic surface cover within a small spatial scale (*Nachabe et al.,* 2005).

Moreover, in some forest covered shallow groundwater areas of the Hungarian Great Plain, *ET* was determined to be larger than precipitation using remote sensing based *ET* estimation techniques (*Szilágyi et al.,* 2012). The deep root system of forests can often tap the shallow groundwater level (if it exists), thus leading to high *ET* that frequently exceeds precipitation. In these groundwater discharge areas, the average annual *ET* was about 70–80 mm more than the mean annual precipitation rate of the region. This negative water balance can be maintained if forests create a local depression in the water table so as to induce groundwater flow directed toward them. Otherwise, forest growing in these groundwater discharge areas possess very good biological productivity, enabling forest management companies to secure a reliable income. As the previous example showed, exact estimation of *ET* in shallow groundwater areas are important not only from a water resources viewpoint, but also from an ecological and economic viewpoint as well.

In areas with a high aridity index (*ETP/P*>1) and a shallow water table, groundwater supplies most of the plant transpiration requirements *(Luo* and *Sophocleous,* 2010; *Loheide et al.,* 2005; *Gribovszki et al.,* 2008; *Nachabe et al.,* 2005).

In these shallow water table environments, transpiration of plants induces a diurnal signal not only in the water table, but in soil moisture as well. *Haise* and *Kelley* (1950) first described a diurnal signal of the soil moisture profile in their tensiometer experiments. These fluctuations can be observed mostly in groundwater discharge areas (*Gribovszki et al.,* 2010; *Móricz et al.,* 2012).

The direct driving force of the signal in the growing season is evapotranspiration (during rainless periods the latter is dominated by transpiration), and the signal is regulated by relative humidity and radiation. The evapotranspiration-induced diurnal signal (in soil moisture and groundwater) has

an early morning maximum and a late afternoon minimum (*Fig. 1*). *Gribovszki et al.* (2010) prepared an elaborate review about this signal and the characteristics of it.
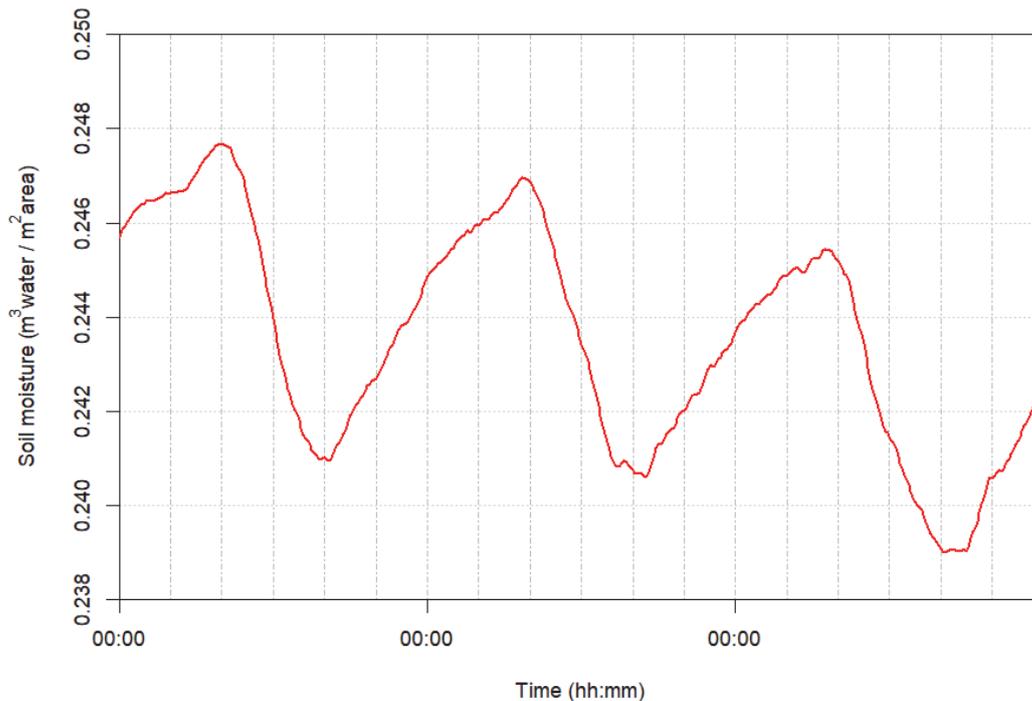

Fig. 1. Typical diurnal pattern in soil moisture induced by evapotranspiration.

White (1932) developed a method that uses observations of the groundwater diurnal signal to calculate plant groundwater uptake. Use of this technique and its modifications is frequent for *ET* estimation (*Bauer et al.*, 2004; *Dolan et al.*, 1984; *Engel et al.*, 2005; *Gribovszki et al.,* 2008; *Loheide,* 2008; *Mould et al.,* 2010; *Reigner,* 1966; *Schilling,* 2007, *Soylu et al.,* 2012, *Gribovszki et al.,* 2010); nevertheless, specific yield estimation remained a weak point of the groundwater signal based methods.

Nachabe et al. (2005) used the *White* (1932) approach for high frequency soil moisture profile data, thereby eliminating the application of the specific yield. *Gribovszki* (2014) modified the *Nachabe et al.* (2005) technique by adapting the empirical version of *Gribovszki et al.* (2008) method, taking into account the diurnally changing replenishment rate from the water table to the vadose zone. The main objective of this paper is to validate the new diurnal soil moisture based technique (which calculates diurnally changing replenishment rate (*Gribovszki,*

2014) using reference *ET* estimations and compare this new method with the White approach (which calculates constant replenishment rate all along the day (*Nachabe et al.,* 2005)) and traditional technique (which does not calculate any replenishment rate (*Dingman*, 2002)).

2. Matherial and methods

The dataset used for ET estimation originated from a valley location (47°40'20"N, 16°27'42"E) of the Hidegvíz Valley experimental catchment in western Hungary (*Fig. 2*).

HIDEGVÍZ VALLEY
EXPERIMENTAL CATCHMENT

SOIL MOISTURE MEASUREMENT

500 m

MET. STATION

LEGEND:
— WATERSHED BOUNDARY
— FOREST ROAD
— STREAM
⊙ METEOROLOGICAL STATION
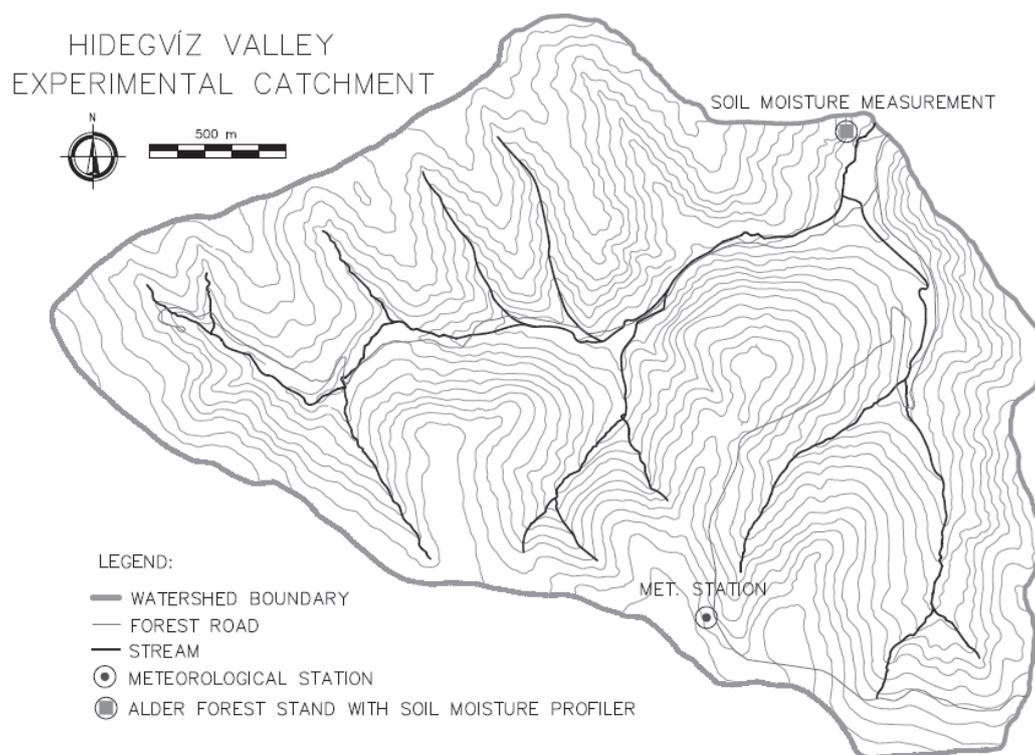◉ ALDER FOREST STAND WITH SOIL MOISTURE PROFILER

Fig. 2. Location of the study site at the outlet point of the experimental catchment.

There are fluvial sediments deposited on the crystalline bedrock in the research area. Over the slopes and hilltops, an unclassified formation in a 10–50-m-thick layer exists. A finer-grained sandy layer, which is a good aquifer, appears in the valleys (*Kisházi* and *Ivancsics,* 1985).

The experimental plot is in a valley bottom, and the soil type there (groundwater discharge area) is loamy sand. The average physical properties of the soil profile are the following: saturated hydraulic conductivity $k=0.18$ m/d; saturated moisture content $\theta_{sat}=0.51$; field capacity at 0.33bar $\theta_{fc}=0.28$.

The vegetation of the experimental plot is a typical phreatophyte azonal ecosystem dominated by alder (Alnus glutinosa (L.) Gaertn.). The mean height of the middle-aged riparian forest stand is about 15 m with a mean trunk diameter of 13 cm (at a height of 1.3 m). The leaf area index (*LAI*) of this forest stand in the growing season was approximately 7.

The area enjoys a sub-alpine climate, with daily mean temperatures of 17 °C in the summer, and with an annual precipitation of 750 mm (*Marosi* and *Somogyi*, 1990). A more detailed description of the area can be found in *Gribovszki et al.* (2006).

2.1. Soil moisture and groundwater data sampling

Six soil moisture capacitive sensors were implemented at 10, 20, 30, 40, 60, and 100 cm below the ground surface in a riparian alder forest (*Fig. 2*). Sensors provide volumetric water content ranging from oven dryness to saturation with accuracy of ± 0.06 m^3/m^3. Soil moisture values were collected every 10 minutes. These data were used for estimation of total soil moisture of the unsaturated soil profile using the following equation:

$$\theta_T = \int_0^{z_0} \theta dz, \tag{1}$$

where θ_T is the total soil moisture (m), z is the depth (m) below the ground surface, and θ is the water content (m^3 water in m^3 soil). For z_0 we used 1.2 m as an arbitrary depth regarding *Fig. 3*, because it is always below the water table even during the growing season.

A groundwater well dataset showed that the groundwater depth in the riparian zone varied between 0.8 to 1.1 m during typical drought periods (*Fig. 3*). Consequently, the tree root system is in direct contact with the saturated zone or, at the very least, with the capillary fringe throughout the year in this shallow water table environment (*Shah et al.*, 2007).

For the analysis, we used the rainless periods in the summer of 2013 (altogether 89 days). 30-minute estimates were compared in selected completely rainless periods. For daily comparison, we selected days with less than 3 mm of precipitation. Rain events below this threshold did not present significant disturbance in the soil moisture diurnal signal; therefore, they did not cause problems for *ET* calculation. The canopy catches the precipitation from these light rain events completely.
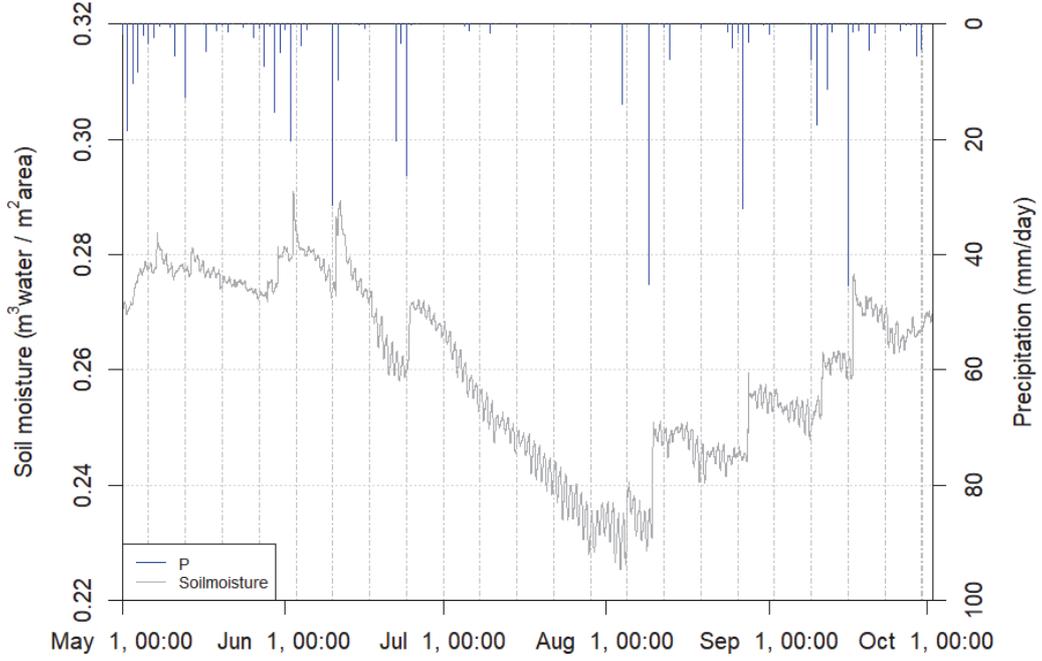
Fig. 3. Soil moisture and precipitation time series for the 2013 growing season.

For *ET* estimation, very accurate soil moisture measurements with relatively high frequency are crucial. Whenever the original measurements are inaccurate, differentiation of the soil moisture record may invoke large errors in the estimations. The application of a low-pass filter (smoother) is recommended to reduce uncertainty. Care must be taken not to "over-filter" the time series, because this can lead to the loss of important details about the process of the diurnal fluctuations. We used 30-min data for the analysis, and the sampling interval was 10 min.

2.2. Theoretical basis of ET estimation

The basic expression of *ET* estimation is the water balance equation for the soil moisture profile:

$$\frac{dS_{sm}}{dt} = \frac{d\theta_T}{dt} = Q_i - Q_o - ET = Q_{net\_sm} - ET, \tag{2}$$

where S_{sm} (m³/m²) is the stored volume of water in the soil moisture profile in a unit area, which is the same as θ_T is the total soil moisture in soil profile (m³/m²), Q_i is the incoming and Q_o is the outgoing water flux (m³/s/m²) to and from the soil column, $Q_{net\_sm} = Q_i - Q_o$ is the net flux/replenishment rate (m³/s/m²), and *ET* is the evapotranspiration (m³/s/m²).

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The soil moisture of the riparian zone, which is directly connected to the water table in discharge zones of shallow groundwater environments, generally meets the transpiration demand of vegetation. In drought periods, groundwater typically replenishes the soil moisture used by evapotranspiration. Around the timing of the soil moisture extrema, when $dS_{sm}/dt = 0$, the net flux, Q_{net_sm} and the ET demand, are in an equilibrium in Eq. (2). $dS_{sm}/dt > 0$ and $Q_{net\_sm} > ET$ on the rising limb and $dS/dt < 0$ and $Q_{net\_sm} < ET$ are on the falling limb of the soil moisture hydrograph. The ET rate is largest during the day when the soil moisture curve is approximately the steepest on the falling limb, which is typically close to the radiation maxima. The smallest ET rate, however, does not necessarily take place when the rising limb of the groundwater level signal is the steepest, but rather just prior to dawn when vapor pressure deficit is at its diurnal minimum. The minima in the soil moisture is accompanied by the steepest hydraulic gradients, so when ET starts to decrease, the steep hydraulic gradient can deliver water to the vadose zone very efficiently, replenishing it fastest right after the occurrence of the soil moisture minimum.

2.3. Traditional method

Traditionally, soil moisture data on a daily time step can be used for ET (ET_{trad}) calculation (*Dingman,* 2002). The calculation process follows the rearranged Eq. (2) neglecting the net flux rate in a daily time step:

$$ET_{trad} = \frac{d\theta_T}{dt}\bigg|_{daily} = \theta_{T(j)} - \theta_{T(j-1)}, \tag{3}$$

where $\theta_{T(j)}$ is the total soil moisture of the jth day, $\theta_{T(j)}$ is the total soil moisture of the $(j-1)$th day. Eq. (3) neglects the replenishment rate from below. This is true only in circumstances where the water table is deep enough to prevent root contact.

2.4. Traditional diurnal method (White approach)

White (1932) worked out a method of estimating ET rates on a daily time step based on diurnal fluctuations of the water table. *Nachabe* (2005) adapted this method for total soil moisture of the vadose zone, thereby eliminating the difficulty of estimating the specific yield, which was the limitation of the original White approach and all other groundwater fluctuation based methods.

Using the original *White* (1932) approach, *Nachabe* (2005) assumed that during the predawn/dawn hours, when ET is negligible, the rate of the observed total soil moisture increase is directly proportional to the net flux rate (it represents the rate of water supply to a unit area). The slope of the tangential line (Q_{netmin_sm} ($m^3/s/m^2$)) drawn to the total soil moisture level curve in these sections was determined. By extending the tangential line over a 24-hour period and taking the

difference in total soil moisture, one would obtain an estimate of the total water supply to the unit area over a day. The daily rate of water supply obtained thus (replenishment rate) must typically be modified by $d\theta_T/dt_{daily}$ ($m^3/s/m^2$), the difference in the observed soil moisture over the 24-hour period, since it is rare for soil moisture to return to the same elevation it had the day before. Otherwise, the $d\theta_T/dt_{daily}$ value is the same as the evapotranspiration from traditional estimates (ET_{trad}) regarding Eq. (3).

In this way, the daily ET rate is obtained by

$$ET_{white\_sm} = 24 \cdot Q_{netmin\_sm} + \frac{d\theta_T}{dt}_{daily}. \tag{4}$$

It is worth noting that the White approach assumes a constant net supply rate throughout the day. This flux is estimated in the predawn/dawn hours when ET is close to zero and the supply rate is the smallest for the day.

2.5. New diurnal method (diurnally changing replenishment rate)

The water table diurnal signal was used for ET_{gw} (evapotranspiration from groundwater) estimation by *Gribovszki et al*. (2008). This approach takes into account a diurnally changing replenishment rate, not a constant one as *White* (1932) had supposed earlier. The theory of the groundwater diurnal signal based method *Gribovszki* (2014) applied for ET calculation used soil moisture data.

The steps of the new ET estimation approach are the following. First, the total soil moisture is differenced in time (half-hourly or hourly time steps are convenient) to obtain $d\theta T /dt$. The new time series (*Fig. 4*) symbolizes the difference between water supply (Q_{net_sm}) and demand (ET) over the soil profile. At night when ET is almost zero, Q_{net_sm} can be calculated using the simplified water balance:

$$\frac{d\theta_T}{dt} = Q_{net\_sm}. \tag{5}$$

To get a continuous time series of the net flux (Q_{net_sm}) through the course of the whole day, a so-called empirical sub-method theory developed for the groundwater diurnal signal (*Gribovszki et al.,* 2008) was adapted for soil moisture data (*Gribovszki,* 2014).

The maximum of Q_{net_sm} for each day was calculated by selecting the largest positive value from differential total soil moisture ($Q_{netmax\_sm} = max(d\theta_T/dt)$), while the minimum was obtained by calculating the mean value from $d\theta_T/dt$ taken in the predawn/dawn hours ($Q_{netmin\_sm} = mean(\theta_{Tpredawn}/dt)$). Averaging is necessary to minimize the relatively large role of measurement error may play at dawn when the changes of soil moisture are small. The obtained values of the Q_{net_sm} then were assigned to those temporal locations where the soil moisture

extrema took place (Q_{netmax_sm} to the time of soil moisture minima and Q_{netmin_sm} to the time of soil moisture maxima). This was followed by a spline (or when the data are very noisy a linear) interpolation of the Q_{net_sm} values to derive intermediate values between the specified characteristic points (*Fig. 4*).
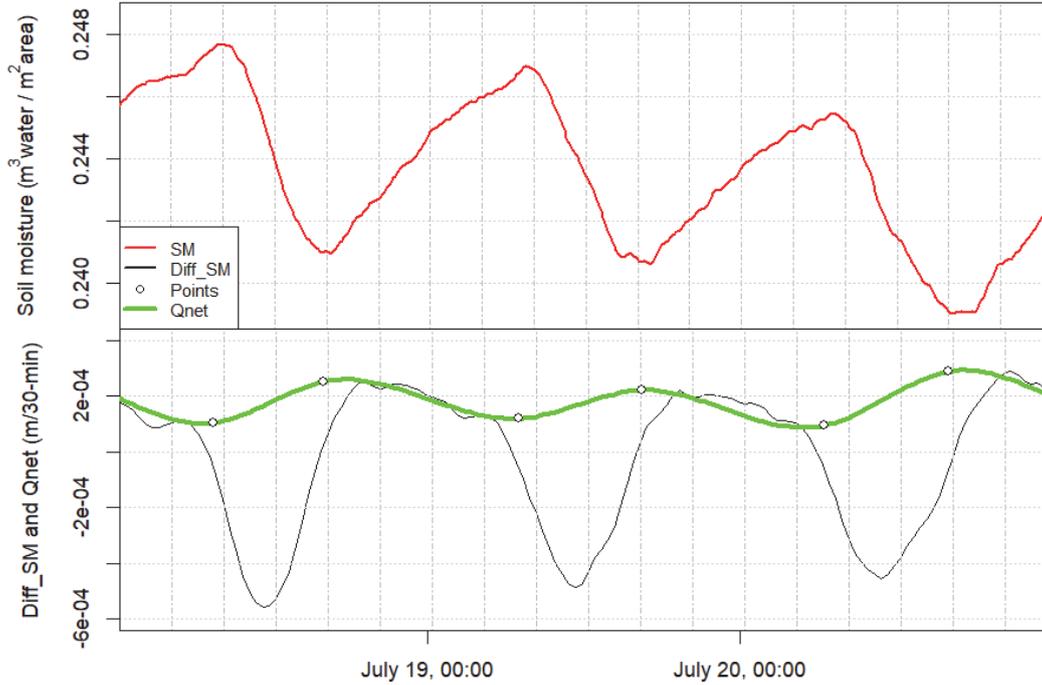

Fig. 4 The principle of the proposed method (*SM:* soil moisture, *Points:* characteristic points, *Qnet:* replenishment, *Diff_SM:* differential soil moisture) for some selected days.

ET rates from soil moisture signal considering a diurnally changing replenishment rate can be obtained by rearranging the former water balance equation (Eq. (2)) as

$$ET = Q_{net\_sm} - \frac{d\theta_T}{dt}. \tag{6}$$

2.6. Reference ET calculation

Different *ET* estimations were compared to reference *ET* determined by the Penman-Monteith (*PM_ET*) method (*Allen et al.,* 1998). This method is one of

the most reliable methods in estimating evapotranspiration from densely vegetated surfaces as

$$PM\_ET = \frac{\Delta(R_0 - S) + \rho\, c_p VPD\, r_a^{-1}}{L_v[\Delta + \gamma \cdot (1 + r_c r_a^{-1})]},$$ (7)

where PM_ET is the Penman–Monteith ET (mm time_step^{-1}), L_v is the latent heat of vaporization (MJ kg^{-1}), Δ is the slope of the saturation vapor pressure curve (kPa °C^{-1}), γ is the psychrometric constant (kPa °C^{-1}), R_0 is the net radiation (MJ m^{-2} time_step^{-1}), VPD is the vapor pressure deficit (kPa), S is the soil heat flux and temporary storage of energy into the tree itself (MJ m^{-2} time_step^{-1}), ρ is the air density (kg m^{-3}), c_p is the specific heat of moist air (kJ kg^{-1} °C^{-1}), r_a is the aerodynamic resistance (s m^{-1}), and r_c is the bulk canopy resistance (s m^{-1}).

The meteorological data for PM_ET calculation originated from climate station sensors located 2 m above the forest canopy, 1.6 km away from the soil moisture measurement site.

The tree canopy is 10–15 m above the soil surface at the study site, so soil heat flux contributions to the available energy for the canopy were considered very small. Temporary energy storage in tree stems and twigs was estimated at 5% of the solar radiation (*Goodrich et al., 2000*). *Goodrich et al.* (2000) also offered a high r_c value (i.e., 5000 s m^{-1}) for the night in order to cease ET at night. This high resistance value is not always realistic, because nocturnal sap flow can be as high as 10–25% of the daily ET in some situations (*Gazal et al., 2006*). Therefore, positive ET at night, as our estimates in some cases suggest (*Fig. 5*), can be realistic. Seasonal changes of the r_c value were estimated using *LAI* measurements ($r_c = 200/ LAI$ (*Allen et al.,* 1998)) during the summer. In our case, Penman–Monteith estimates represent ''real world'' ET of well-watered forest vegetation that can be used as a benchmark to compare with the proposed methods. ET values produced by the new method were compared with those of the Penman–Monteith method at a 30-min resolution, of the traditional, and of the White approach-based methods on a daily basis.

For comparison of different ET estimations, the Tukey HSD (honestly significant difference) post hoc test and correlation test were used in an R software environment (*R Core Team,* 2012).
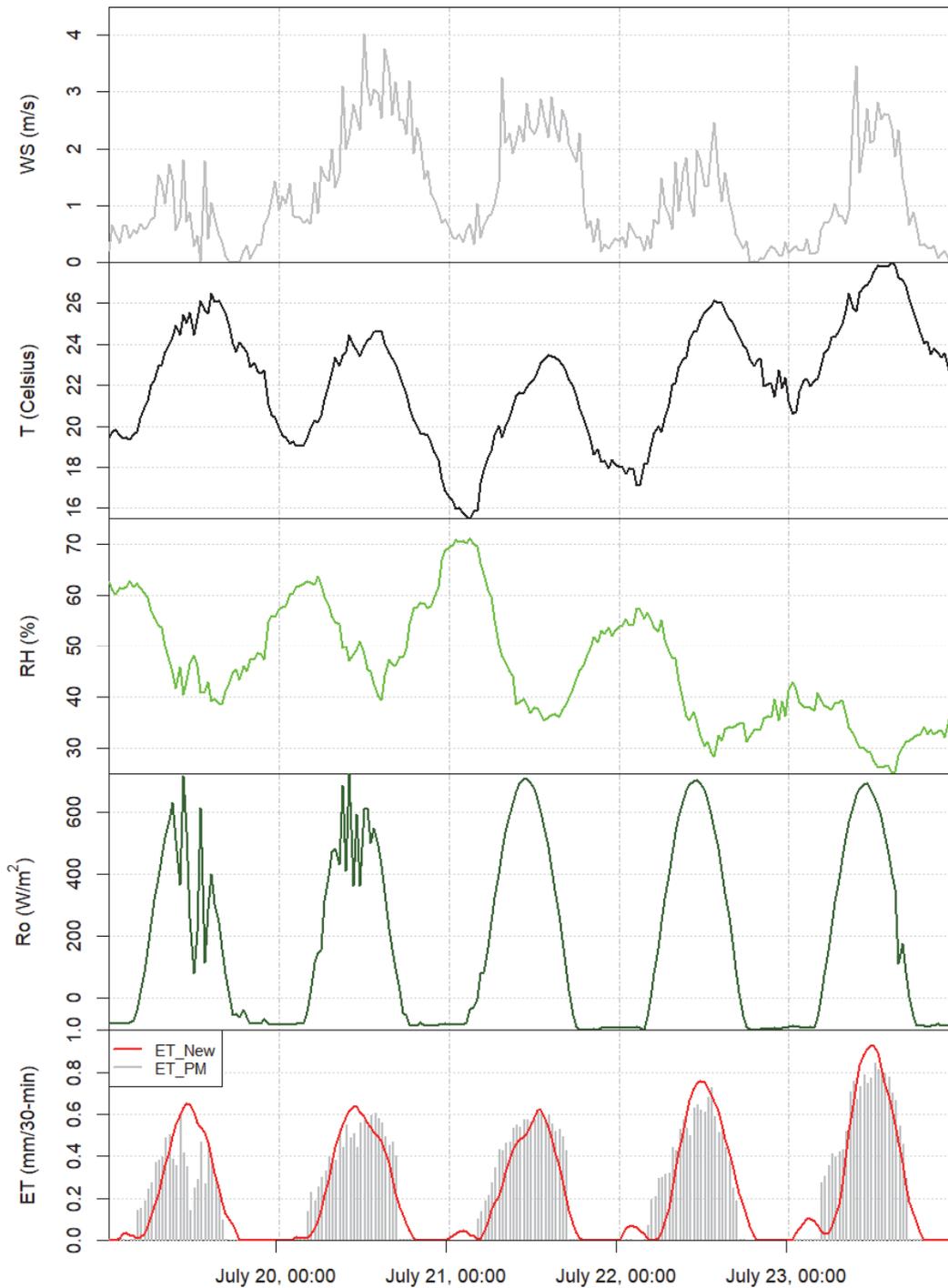
Fig. 5 Half hourly evapotranspiration estimates of new soil moisture based [*ET_New*] and PM [*ET_PM*] methods plotted together with meteorological parameters [*WS*: wind speed, *T*: temperature, *RH*: relative humidity, R_0: net radiation] for some selected days

3. Results and discussion

Half-hourly *ET* estimates of the new method are compared with the *PM_ET* values in three selected rainless periods (June 3–9, 2013, July 16 – August 5, 2013,

September 1–8, 2013). *Fig. 5* illustrates *ET* values for some selected days at the end of July together with meteorological parameters.

Cross-correlation analysis of the half-hourly *ET* values (between the Penman–Monteith and the new method) show a peak ($r = 0.854–0.914$) generally at a separation distance of 30–60 min with the new method's values lagging behind those of the Penman–Monteith approach. Larger lag time is more typical closer to the start (at the beginning of June) and at the end (in September) of the growing season. The lag can be the consequence of the delayed transport mechanism in the xylem from the roots to the leaves. The travel time of the water particle allows some difference between the time of the transpiration and absorption of water from the soil.

Fig. 6 displays the estimated *ET* rates on a daily basis, obtained by daily calculation (White and traditional estimates) and by summing the 30-min values over the days (PM and proposed diurnal method estimates). By using new diurnal method for *ET* estimation, a better correlation (0.85) can be found with *PM_ET* values than when White approach (0.76) and traditional estimates (0.38) were applied. Not only the correlation was better, but the absolute values for *ET* (*ET_New*) are also much closer to *PM_ET* as *Table 1* shows.
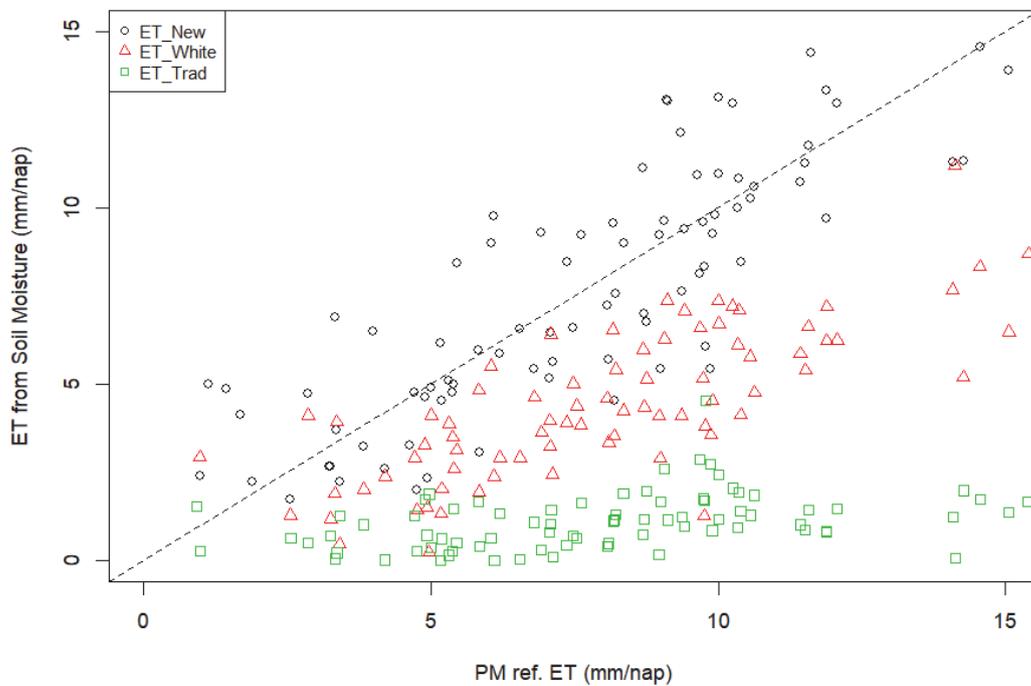

Fig. 6. ET values of different soil moisture-based methods versus *PM_ET* values as a reference method (*ET_New:* diurnal proposed method – black circles, *ET_White:* White approach – red triangle, *ET_Trad:* traditional method – green squares).

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Table 1. ET values from different methods (*n=89*)

Method	Mean (sd) (mm d⁻¹)	Diff from *ET_PM* (mm d⁻¹)	Tukey HSD test p-value*	correlation with *ET_PM*
ET_PM	7.21 (3.73)	–	–	–
ET_New	7.84 (3.66)	0.63	0.4341	0.846
ET_White	4.43 (2.11)	2.78	0.0000	0.762
ET_Trad	1.11 (0.79)	6.10	0.0000	0.379

sd: standard deviation, p-value*: Tukey HSD test significance compared with *ET_PM*.

The Tukey HSD test result shows (*Table 1*) that only the proposed, new method does not differ significantly from *PM_ET*. The White approach underestimates reference *PM_ET* by 38%, while traditional calculation gives only 1/6–1/7 of the Penman-Monteith values.

The explanation of the deviations between the different assumptions is the following:

The original White approach assumes a constant replenishment rate to the vadose zone throughout the day. The replenishment is estimated when *ET* is close to zero in the late night hours, when the net flux is reduced due to a diminished hydraulic gradient. Contrasting the new method accounts for this diurnal change of the replenishment rate, which has a maximum when *ET* is most intensive and a minimum in the morning hours.

The traditional method does not take into account any replenishment from below; thus, the estimated *ET* values of that approach are very low. The relative importance of the net flux can be up to 90% of the *ET* rates (*Gribovszki,* 2014); therefore, neglecting this rate from below very significantly distorts the estimated *ET*.

Comparing *ET* from the new method (7.8 mm d⁻¹) with results of other studies, it can be stated that these values typically represent the high-end of those estimates. It is worth noting that only dry and hot periods of the vegetation season were used for estimations of *ET*. *Nachabe et al.* (2005) calculated monthly average total *ET* rates of 1.5–6.3 mm d⁻¹ for a forest with the help of continuous soil moisture profile measurements in Florida using the White approach. *Gazal et al.* (2006) found *ET* as 2–7 mm d⁻¹ for a cottonwood forest in semiarid region of Australia. *Goodrich et al.* (2000) obtained 4–8 mm d⁻¹ *ET* values for mixed vegetation, while *Hughes et al.* (2001) found 2–6 mm d⁻¹ *ET* rates for a temperate salt marsh in Australia. In the cases of the last three research studies, sap flow measurements and micrometeorological methods were employed for calculating total *ET*. Important vegetation parameters (such as *LAI*) cannot always be deduced from these previous studies; therefore, comparison is not straightforward with

present estimates. Notwithstanding, the new *ET* estimation seems to yield realistic values. Especially when one considers the ready access of vegetation to vadose zone soil moisture directly connected with the shallow water table, the abundance of available energy in the growing season considered, as well as a large value of *LAI*, all combined with a favorable match with the Penman–Monteith *ET* values as a control. *ET* estimates of the new method seem also to be acceptable if the oasis effect (*Morton,* 1983) is taken into account in a well-watered valley situation, in a period when a hot and dry environment can add a significant amount of heat enhancing *ET*.

4. Conclusions

The current *ET* estimation method is an enhanced version of the original *White* (1932) method adapted to soil moisture diurnal signal measured with high frequency.

The new method has been successfully validated using a well-known Penman-Monteith approach. Penman-Monteith *ET* values show a good correlation with present estimates; deviations between the reference and proposed method are small, not only on daily, but also on half-hourly scale. The estimated relatively high evapotranspiration values seem to be acceptable if the oasis effect is taken into account. Compared to traditional approaches and the White approach based diurnal techniques for soil moisture data, this new method gives significantly higher *ET* rates by taking into account continuous, diurnally changing soil moisture replenishment from shallow groundwater to the vadose zone.

The advantage of this new soil moisture-based diurnal technique over the groundwater signal based estimates is that only a soil moisture profile dataset is needed for the calculation of *ET,* and there is no need for specific yield (the most problematic parameter of groundwater diurnal signal based methods) values of a given soil profile.

The proposed method has potential benefits for determining *ET* rates in a changing climate with warmer and drier growing seasons. The *ET* of well-watered vegetation in groundwater discharge areas in hot and dry environments will probably increase in the future. The used water amount has a strong connection to biological productivity, and precise determination of *ET* from those areas is important from a water resources protection point of view as well.

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